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ARTI REFRIGERANT DATABASE

PRIMARY AND RECENTLY-ADDED CITATIONS

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prepared by

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for the

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INTRODUCTION

This report provides citations and summaries from the *ARTI Refrigerant Database* from the *Recently Added and Key Citations* file. It is one of a series prepared to provide a record of the database entries in printed form.

Purpose

The Refrigerant Database is an information system on alternative refrigerants, associated lubricants, and their use in air conditioning and refrigeration. It consolidates and facilitates access to property, compatibility, environmental, safety, application and other information. It provides corresponding information on older refrigerants, to assist manufacturers and those using alternative refrigerants, to make comparisons and determine differences. The underlying purpose is to accelerate phase out of chemical compounds of environmental concern.

Contents

The database provides bibliographic citations and abstracts for publications that may be useful in research and design of air-conditioning and refrigeration equipment. The complete documents are not included, though some may be added at a later date.

The database identifies sources of specific information on R-22, R-23, R-32, R-41, R-116, R-123, R-124, R-125, R-134, R-134a, R-141b, R-142b, R-143a, R-152a, R-218, R-227ea, R-236fa, R-245ca, R-245fa, R-290 (propane), R-C318, R-717 (ammonia), R-718 (water), R-744 (carbon dioxide), R-1270 (propylene), ethers, and others as well as azeotropic and zeotropic blends of these fluids. These blends include R-400, R-401A, R-401B, R-401C, R-402A, R-402B, R-403A, R-403B, R-404A, R-405A, R-406A, R-407A, R-407B, R-407C, R-407D, R-408A, R-409A, R-409B, R-410A, R-410B, R-411A, R-411B, R-412A, R-413A, R-414A, R-414B, R-415A, R-416A, R-500, R-501, R-502, R-503, R-504, R-505, R-506, R-507A, R-508A, R-508B, R-509A, and others for which information is available even though standard designations may not have been assigned yet. It addresses lubricants including alkylbenzene, polyalkylene glycol, polyolester, and other synthetics as well as mineral oils. It also references documents addressing compatibility of refrigerants and lubricants with metals, plastics, elastomers, motor insulation, and other materials used in refrigerant circuits.

Incomplete citations or abstracts are provided for some documents. They are included to accelerate availability of the information and will be completed or replaced in future updates.

Limitations

The Refrigerant Database is intended as a means to assist users in locating sources of information on alternative refrigerants. But, the database is:

- neither a comprehensive nor authoritative reference source,
- not a substitute for independent data collection by users,
- not a substitute for examination of the data, information on how they were arrived at, assumptions, and caveats in the cited documents, and
- not an endorsement of suitability or accuracy of referenced publications.

Materials compatibility, properties, safety considerations, and other characteristics affecting suitability or desirability may be influenced by a number of factors. Among them are specific application conditions, preparation such as drying before use, additives including fillers, impurities, catalytic interactions with other materials used, and changes in compounding between one source or batch and another. Similarly, new findings or corrections may supersede previously published data. The database is an aid in locating data that may be pertinent; it is not and should not be viewed as the source of data for research, design, analysis, or other purposes.

Database Form

The database is available in both computerized ("electronic") and report ("manual" or "listing") versions.

Computerized Version

The computerized version includes both data summaries and bibliographic citations organized into a number of segments ("files"). These segments can be searched individually or together, in any combination.

The computerized database provides 606 specially-prepared data summaries, including refrigerant (single compound and blend) profiles, tabular compatibility summaries for plastics and elastomers, and toxicity reviews for refrigerants. The refrigerant profiles cover designations, common uses, chemical and trade names, other identifiers, molecular mass, critical properties (pressure, temperature, specific volume, and density at the critical point), physical and thermophysical properties for selected conditions, safety classifications, toxicity and flammability data, exposure limits, atmospheric lifetime, ozone depletion potential, global warming potential, halogen global warming potential, commercialization, phaseout, and other data.

The computerized version also provides more than 6,100 citations. They are organized into a primary file that includes recently added and key references, a supplement on copper in air

Distribution of the Refrigerant Database

	computerized (diskette)	report (listing)	documents (copies)
data summaries			
• refrigerant profiles	yes	no	[a]
• compatibility	yes	no	[a]
• toxicity	yes	no	[a]
bibliographic citations and synopses (detailed abstracts)			
• recently added and key	yes	yes	[a]
• copper supplement [b]	yes	[b]	[a]
• archival and historical	yes	no	[a]
search and retrieval software	yes [c]	no	no
additions and changes flagged	no	yes	no
distributed on cost-recovery basis			
• subscription (periodic updates)	yes	yes	no
• as ordered	no	yes	yes [d]

[a] Data summaries, citations, and synopses may be printed with the computerized version.

[b] The Copper Development Association (CDA) sponsored supplement provides additional citations and synopses, most of which address compatibility with or use of copper in air-conditioning and refrigeration systems. The supplement is included and searchable with the computerized version, but published as a separate report.

[c] Use of the search and retrieval software is subject to acceptance of the license agreement for it; both accompany the computerized version.

[d] Distribution is limited to documents in the public domain or for which authorization has been obtained. Others may be ordered from their publishers, which are identified in the bibliographic citations.

conditioning and refrigeration, and an archival group covering historical and superseded documents.

The search and retrieval software provided with the computerized version enables very fast searches for user-selected terms or combinations of terms. The search program offers several automated features to simplify use. They include optional prompting by search category, an automated "thesaurus" of synonyms and related terms, chain searches to broaden or narrow prior searches, a "wildcard" capability to allow entry of word segments, and a configuration capability to customize a number of options. The program also allows printing of selected portions of the database. Printing the entire database would yield more than 8,000 pages, so a printed version is available for those who prefer to use the database manually.

Report Version

A listing of the recent and key citations is provided in report form. The citations are grouped under the primary or first subject addressed; they are not cross-referenced under other topics. The computerized version, therefore, is better suited to search for information by subject.

Citations and summaries from the supplement on copper in air conditioning and refrigeration are published separately. They also are arranged by subject.

Archival and historic citations are included in a third report. They are presented in reverse chronological order, beginning with the most recent. These citations remain accessible through the computerized version.

Documents

The database also includes a collection of published and unpublished documents, copies of which can be ordered individually. Approximately one third of the documents cited in the database are included in this collection. They include documents that are not protected by copyright or proprietary restrictions. They also include documents for which the authors or copyright owners granted permission for reproduction and distribution. The remainder can be obtained from their publishers, libraries, and other sources (see page 6).

Ordering Information

The computerized version of the database and the report version for recently added and key references can be ordered along with a subscription for updates. The report versions of the copper supplement and the archival citations report are available as separate documents distributed through the database.

An order form for the Refrigerant Database, which indicates the pricing, accepted methods of payment, and applicable terms and conditions, may be downloaded from the Internet from *http://www.arti-21cr.org/db/qa.html*. Alternatively, a copy may be obtained by mail or fax by calling +1-703/524-8800 or faxing +1-703/522-2349. Questions should be sent by email to *database@spectrum-internet.com.* Please note that the same form may be used to obtain the computerized database and remaining scheduled updates, the report version and remaining scheduled updates for primary and key references, and database documents by completing the corresponding portions of the form.

Additions

Future updates and expansions to the database are planned. Please help in making it more useful, and facilitating use of alternative refrigerants, by submitting the following:

- corrections to errors identified in the database,
- copies of helpful papers - whether your own or written by others - for citation, and
- suggestions for improving the database.

Authors or those holding rights to published or unpublished works pertinent to the database are invited - and encouraged - to authorize their reproduction and unrestricted distribution through the database. Product literature normally is not included, but studies providing relevant information, whether on proprietary or generic substances, will be considered.

Please send your inputs to:

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Thank you for your help with and use of the database. Its objective is to accelerate phase out of chemical compounds of environmental concern by sharing the information needed to do so.

Obtaining Documents

Documents indicated as *available from JMC* in their citations are available through the database. An order form, which indicates the pricing, accepted methods of payment, and applicable terms and conditions, may be downloaded from the Internet from *http://www.arti-21cr.org/db/qa.html*. Alternatively, a copy may be obtained by mail or fax by calling +1-703/524-8800 or faxing +1-703/522-2349. Questions should be sent by e-mail to *database@spectrum-internet.com*.

Other documents should be ordered from their publishers or alternative sources as identified in the database. Many of these documents also may be obtained from libraries. An effort will be made to secure permission for JMC to distribute additional documents, to facilitate access to them, but compliance with copyright provisions precludes doing so until appropriate arrangements are made. Reports from national laboratories and the Gas Research Institute may be ordered from the NTIS; most other publications from the U.S. Government may be obtained from the GPO. Addresses for several alternative sources follow:

ACGIH American Conference of Governmental Industrial Hygienists, 1330 Kemper Meadow Drive, Suite 600, Cincinnati, OH 45240 USA; phone +1-513/742-2020, fax +1-513/742-3355, e-mail acgih_pubs@pol.com.org

AIHA American Industrial Hygiene Association, 2700 Prosperity Avenue, Suite 250, Fairfax, VA 22031 USA; phone +1-703/849-8888, fax +1-703/207-3561; http://www.aiha.org

ARI Air-Conditioning and Refrigeration Institute, 4301 North Fairfax Drive, Suite 425, Arlington, VA 22203 USA; phone +1-703/524-8800, fax +1-703/528-3816; http://www.ari.org

ASHRAE Publication Sales, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1791 Tullie Circle NE, Atlanta, GA 30329 USA; phone +1-404/636-8400, fax +1-404/321-5478, e-mail orders@ashrae.org

CAS Chemical Abstracts Service, Document Delivery Department, Post Office Box 3012, Columbus, OH 43210-0012 USA; phone + 1-614/447-3670 x2956 (from USA 800/848-6538) , fax + 1-614/447-3648

EHIS Environmental Health Information Service, OCR Subscription Services Incorporated, Post Office Box 12510, Research Triangle Park, NC 27709-2510 USA; phone +1-919/541-3841, fax +1-919/541-0273, e-mail: ehis@niehsnih.gov

EPRI EPRI Distribution Center, 207 Coggins Drive, Post Office Box 23205, Pleasant Hill, CA 94523 USA; phone+ 1-510/934-4212

GPO Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402 USA; phone + 1-202/512-1800

IIR / IIF Institut International du Froid, 177, Boulevard Malesherbes, F-75017 Paris, France; phone +33-1 / 42.27.32.35, fax +33-1 / 47.63.17.98, e-mail iifiir@ibm.net

JAR Japanese Association of Refrigeration, Nippon Reito Kyokai, 4th Floor, San-ei Building, 8 San-ei-cho, Shinjuku-ku, Tokyo 160, Japan; phone +81-3/3359-5231, fax +81-3/3359-5233

JMC James M. Calm, Engineering Consultant, 10887 Woodleaf Lane, Great Falls, VA 22066-3003 USA, fax+ 1-703/450-4313, e-mail database@spectrum-internet.com

JSRAE Japan Society of Refrigerating and Air Conditioning Engineers, Sanei Building, 8 Sanei-cho, Shinjuku-ku, Tokyo 160-0008, Japan; phone +81-3/3359-5231, fax +81-3/3359-5233

LHL Linda Hall Library of Science, Engineering, and Technology, 5109 Cherry Street, Kansas City, MO 64110-2498 USA; phone + 1-816/363-4600, fax + 1-816/926-8785, e-mail requests@lhl.lib.mo.us

NTIS National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161 USA; phone +1-703/487-4780

SAE Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, PA 15096-0001 USA

REFRIGERANT DATABASE - CITATIONS AND ABSTRACTS

THERMOPHYSICAL PROPERTIES

E. M. Clark (DuPont Fluorochemicals) and M. O. McLinden (National Institute of Standards and Technology, NIST), **Refrigerants**, *ASHRAE Handbook - Fundamentals* (published in separate editions with inch-pound and SI metric units), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, chapter 18, 18.1-18.10, 1997 (10 pages with 3 figures and 12 tables, RDB7A01)

This chapter summarizes information on common refrigerants, including designations, physical and electrical properties, performance, safety data, leak detection methods, and effects on construction materials. The refrigerants addressed include R-10, R-11, R-12, R-12B1, R-12B2, R-13, R-13B1, R-14, R-20, R-21, R-22, R-22B1, R-23, R-30, R-31, R-32, R-40, R-41, R-50, R-110, R-111, R-112, R-112a, R-113, R-113a, R-114, R-114a, R-114B2, R-115, R-116, R-120, R-123, R-123a, R-124, R-124a, R-125, R-133a, R-134a, R-140a, R-141b, R-142b, R-143a, R-150a, R-152a, R-160, R-170, R-216ca, R-218, R-245cb, R-290, R-C316, R-C317, R-C318, R-400, R-401A, R-401B, R-401C, R-402A, R-402B, R-403A, R-403B, R-404A, R-405A, R-406A, R-407A, R-407B R-407C, R-407D, R-408A, R-409A, R-409B, R-410A, R-410B, R-411A, R-411B, R-412A, R-500, R-501, R-502, R-503, R-504, R-505, R-506, R-507A, R-508A, R-508B, R-509A, R-600, R-600a, R-610, R-611, R-620, R-630, R-631, R-702n, R-702p, R-704, R-717, R-718, R-720, R-728, R-732, R-740, R-744, R-744A, R-764, R-1112a, R-1113, R-1114, R-1120, R-1130, R-1132a, R-1140, R-1141, R-1150, and R-1270. Molecular mass, normal (atmospheric) boiling point, freezing point, critical properties (temperature, pressure, and specific volume), and liquid refractive index are tabulated for most of these fluids. Dielectric constants, volume resistivity, velocity of sound, latent heat of vaporization, comparative performance, effects of temperature on performance, and safety classifications are presented for some refrigerants. Swell data are tabulated for R-11, R-12, R-13, R-13B1, R-21, R-22, R-30, R40, R-113, R-114, R-502, and R-600 for eight elastomers. They include nitrile butyl rubber (Buna™N), butadiene styrene (Buna™ S, GR-S), Butyl™ (GR-1), natural rubber, neoprene GN, polysulfide rubber (Thiokol(R) FA), fluoroelastomer (DuPont Viton(R) B), and silicone. Diffusion data are tabulated for water and R-22 through neoprene, Buna N, synthetic rubber (DuPont Hypalon(R) 40), Butyl, Viton, polyethylene, and natural rubber. Density, specific heat, and viscosity are plotted for water/lithium bromide solutions (for absorption cycles) as functions of the mass fraction of lithium bromide.

P. E. Liley and P. D. Desai (Purdue University), **Thermophysical Properties of Refrigerants (SI Edition),** publication 90375, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1993 (296 pages with 230 tables, available from ASHRAE for $33 to members and $44 to nonmembers, RDB3A81)

This reference provides detailed specific heat, thermal conductivity, viscosity, velocity of sound, and surface tension data in tabular form in metric (SI) units. The refrigerants addressed include R-11, R-12, R-13, R-13B1, R-14, R-22, R-23, R-50 (methane), R-113, R-114, R-115, R-142b, R-152a, R-170 (ethane), R-290 (propane), R-C318, R-500, R-502, R-503, R-600 (butane), R-600a (isobutane), R-702 (hydrogen), R-702p (para-hydrogen), R-704 (helium), R-717 (ammonia), R-718 (water), R-720 (neon), R-728 (nitrogen), R-729 (air), R-732 (oxygen), R-740 (argon), R-744 (carbon dioxide), R-1150 (ethylene), and R-1270 (propylene). Empirical or semi-empirical property equations also are provided for

please see page 6 for ordering information

R-11, R-12, R-13, R-13B1, R-14, R-22, R-23, R-113, R-114, R-142b, R-152a, R-500, R-502, R-503, R-717, and R-744. More than 200 references are cited to identify the data sources used.

P. E. Liley and P. D. Desai (Purdue University), **Thermophysical Properties of Refrigerants (Inch-Pound Edition),** publication 90373, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1993 (292 pages with 230 tables, available from ASHRAE for $33 to members and $44 to nonmembers, RDB3A82)

This reference provides detailed specific heat, thermal conductivity, viscosity, velocity of sound, and surface tension data in tabular form in inch-pound (IP) units. The refrigerants addressed include R-11, R-12, R-13, R-13B1, R-14, R-22, R-23, R-50 (methane), R-113, R-114, R-115, R-142b, R-152a, R-170 (ethane), R-290 (propane), R-C318, R-500, R-502, R-503, R-600 (butane), R-600a (isobutane), R-702 (hydrogen), R-702p (para-hydrogen), R-704 (helium), R-717 (ammonia), R-718 (water), R-720 (neon), R-728 (nitrogen), R-729 (air), R-732 (oxygen), R-740 (argon), R-744 (carbon dioxide), R-1150 (ethylene), and R-1270 (propylene). Empirical or semi-empirical property equations also are provided for R-11, R-12, R-13, R-13B1, R-14, R-22, R-23, R-113, R-114, R-142b, R-152a, R-500, R-502, R-503, R-717, and R-744. More than 200 references are cited to identify the data sources used.

M. O. McLinden, E. W. Lemmon (National Institute of Standards and Technology, NIST), R. R. Singh (AlliedSignal Incorporated) and K. E. Herold (University of Maryland at College Park), **Thermophysical Properties of Refrigerants,** *ASHRAE Handbook - Fundamentals (*published in separate editions with inch-pound and SI metric units), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, chapter 19, 19.1-19.89, 1997 (89 pages with 41 figures and 52 tables, RDB7A02)

This chapter provides pressure-enthalpy (Mollier) diagrams and tabulates thermodynamic and transport properties for R-11, R-12, R-13, R-13B1, R-14, R-22, R-23, R-32, R-50 (methane), R-113, R-114, R-123, R-124, R-125, R-134a, R-141b, R-142b, R-152a, R-170 (ethane), R-290 (propane), R-404A, R-407C, R-410A, R-500, R-502, R-503, R-507A, R-600 (butane), R-600a (isobutane), R-702 (normal hydrogen), R-702p (parahydrogen), R-704 (helium), R-717 (ammonia), R-718 (water/steam), R-720 (neon), R-728 (nitrogen), R-729 (air), R-732 (oxygen), R-740 (argon), R-744 (carbon dioxide), R-1150 (ethylene), and R-1270 (propylene). The tabular data include temperature, pressure, vapor volume, liquid density, enthalpy, entropy, specific heat, specific heat ratio, velocity of sound, viscosity, thermal conductivity, and surface tension. An enthalpy-concentration diagram and tabular data for the specific volume at saturation are presented for ammonia/water for absorption cycles. Enthalpy equilibrium and concentration diagrams are similarly provided for water/lithium bromide solutions.

R. B. Stewart, R. T. Jacobsen, and S. G. Penoncello (University of Idaho), **ASHRAE Thermodynamic Properties of Refrigerants,** inch-pound (IP) version, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1986 (508 pages with 31 figures and 65 tables, RDB3208)

This book provides detailed thermodynamic property data for 31 refrigerants in inch-pound (IP) units of measure. An introductory section presents the equations of state (EOS), ancillary equations, and references for the data used. Appendices summarize the conversion factors and reference (datum) states for entropy and enthalpy. A sequence containing a pressure enthalpy diagram and two tables follows for each refrigerant. The first table presents saturated properties by temperature including pressure; liquid and vapor specific volume, density, enthalpy, and entropy; and the latent heat of vaporization. The second provides the density, enthalpy, and entropy at unsaturated conditions, by temperature and pressure. The refrigerants covered include R-11, R-12, R-13, R13B1, R-14, R-22, R-23, R-50 (methane), R-113, R-114, R-142b, R-152a, R-170 (ethane), R-290 (propane), R-500, R-502, R-503, R-600 (butane), R-600a (isobutane), R-702 (hydrogen), R-702a (parahydrogen), R-704 (helium), R-717 (ammonia), R-720 (neon), R-728 (nitrogen), R-729 (air), R-732 (oxygen), R-740 (argon), R-744 (carbon dioxide), R-1150 (ethylene), and R-1270 (propylene). Martin-Hou equations of state (EOS), or subsets or extensions thereto, were used for most of the fluorocarbon refrigerants. Detailed formulations were used for R-12 and R-22, and a truncated virial equation was used for R-13B1. Modified Benedict-Webb-Rubin (MBWR) equations were used for R-11, R-50, R-702, R-702a, R-720, R-728, R-732, R-1150, and R-1270. Specific formulations were used for the remainder, notably that by Haar and Gallagher for R-717.

R. B. Stewart, R. T. Jacobsen, and S. G. Penoncello (University of Idaho), **ASHRAE Thermodynamic Properties of Refrigerants,** metric (SI) version, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1986 (466 pages with 31 figures and 65 tables, RDB3209)

This book provides detailed thermodynamic property data for 31 refrigerants in metric (SI) units of measure. An introductory section presents the equations of state (EOS), ancillary equations, and references for the data used. Appendices summarize the conversion factors and reference (datum) states for entropy and enthalpy. A sequence containing a pressure enthalpy diagram and two tables follows for each refrigerant. The first table presents saturated properties by temperature including pressure; liquid and vapor specific volume, density, enthalpy, and entropy; and the latent heat of vaporization. The second provides the density, enthalpy, and entropy at unsaturated conditions, by temperature and pressure. The refrigerants covered include R-11, R-12, R-13, R-13B1, R-14, R-22, R-23, R-50 (methane), R-113, R-114, R-142b, R-152a, R-170 (ethane), R-290 (propane), R-500, R-502, R-503, R-600 (butane), R-600a (isobutane), R-702 (hydrogen), R-702a (parahydrogen), R-704 (helium), R-717 (ammonia), R-720 (neon), R-728 (nitrogen), R-729 (air), R-732 (oxygen), R-740 (argon), R-744 (carbon dioxide), R-1150 (ethylene), and R-1270 (propylene). Martin-Hou equations of state, or subsets or extensions thereto, were used for most of the fluorocarbon refrigerants included. Detailed formulations were used for R-12 and R-22, and a truncated virial equation was used for R-13B1. Modified Benedict-Webb-Rubin (MBWR) equations were used for R-11, R-50, R-702, R-702a, R-720, R-728, R-732, R-1150, and R-1270. Specific formulations were used for the remainder, notably that by Haar and Gallagher for R-717.

R-11

R. T. Jacobsen, S. G. Penoncello, and E. W. Lemmon (University of Idaho), **A Fundamental Equation for Trichlorofluoromethane (R-11)**, *Fluid Phase Equilibria*, 80(11):45-56, 1992 (12 pages, rdb3911)

thermodynamic properties of R-11: fundamental equation (FEQ); equation of state (EOS); thermophysical data

E. A. Kremenevskaya and S. L. Rivkin, **Thermodynamic Properties of Freon-11**, *Teplofizicheskie Svoistva Veshchestv i Materialov* [Thermophysical Properties of Substances and Materials], edited by V. A. Rabinovich, Izdatel'stvo Standartov, Moscow, Russia (then USSR), 4:1-16, 1975 (16 pages, rdb-7C63)

thermodynamic properties of R-11; thermophysical data

S. L Rivkin and E. A. Kremenevskaya, **Investigation of the Density of Freon-11,** *Teploflzicheskie Svoistva Veshchestv i Materialov* [Thermophysical Properties of Substances and Materials], edited by V. A. Rabinovich, Izdatel'stvo Standartov, Moscow, Russia (then USSR), 8:46-64, 1975 (19 pages, rdb7C64

thermodynamic properties of R-11; thermophysical data

Thermodynamic Properties of 'Freon' 11, technical bulletin T-11, E. I. duPont de Nemours and Company, Incorporated, Wilmington, DE, 1965 (rdb6865)

thermodynamic properties of R-11; thermophysical data

R-12

S. G. Penoncello, R. T. Jacobsen, and E. W. Lemmon (University of Idaho), **A Fundamental Equation for Dichlorodifluoromethane (R-12)**, *Fluid Phase Equilibria*, 80(11):57-70, 1992 (24 pages, rdb3912)

thermodynamic properties of R-12: fundamental equation (FEQ), equation of state (EOS); thermophysical data

K. Watanabe (Keio University, Japan), T. Tanaka, and K. Oguchi, **Compressibility and Virial Coefficients of Dichiorodifluoromethane (R-12) with Burnett Apparatus**, *Proceedings of the Seventh Thermophysical Properties Symposium*, American Society of Mechanical Engineers (ASME), New York, NY, 470-479, 1977 (8 pages, rdb7B24)

thermodynamic properties of R-12: equation of state (EOS); thermophysical data

J. T. R. Watson (National Engineering Laboratory, UK), **Thermophysical Properties of Refrigerant 12**, Her Majesty's Stationery Office (HMSO), Edinburgh, UK, 1975 (rdb2A25)

thermodynamic and transport data for R-12

Thermophysical Properties of Refrigerants (R-12, Dichlorodifluoromethane), Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, August 1981 with errata dated 1986 (160 pages with 23 figures and 90 tables, in both Japanese and English, rdb0401)

This comprehensive volume summarizes critical, thermodynamic, transport, physical, chemical, compatibility, and other data available on R-

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12. Included are tabular data and/or plots for PVT properties, enthalpy, entropy, isobaric and isochoric specific heat capacity, specific heat ratio, speed of sound, surface tension, viscosity, kinematic viscosity, thermal conductivity, thermal diffusivity, Prandtl number, solubility, refractive index, dielectric constant, volume resistivity, and dielectric strength. A 32-term polynomial equation of state is presented and compared to other equations and data. Relations also are presented for key equilibrium properties. Data are tabulated for the solubility of R-12 in water, moisture contents of saturated R-12 liquid and vapor, and R-12 in a naphthenic mineral oil. Data, including decomposition products by pyrolysis and hydrolysis rates, are provided on the stability of R-12 in the presence of metals and oil. Linear swell, weight change, and observations are provided for R-12 with plastics including polytetrafluoroethylene (PTFE), tetra-fluoroethylene-hexafluoropropylene copolymer, polyethylene, polyvinyl alcohol, polypropylene, polyvinylchloride (PVC), polyvinylidene chloride, nylon resin, acrylic resin (polymethacrylate), polystyrene, phenolic resin, epoxy resin, acetal resin, cellulose acetate, cellulose nitrate, acryl fiber, and polyester fiber. Linear swell data are tabulated for neat R-12, oil, and a 50/50 mixture with elastomers including neoprene W, neoprene GN, neoprene RT, Buna™ N, Buna™ S, natural rubber, polysulfide rubber, epichlorohydrin rubber, butyl rubber GR-I, chlorosulfonated polyethylene (DuPont Hypalon(R) 40), polyvinyl alcohol (PVA), fluoroelastomers (DuPont Viton(R) A and B), and urethane rubber. Published safety data, including toxicity and flammability, are summarized. The volume contains an extensive list of references as well as discussion of the ranges and differences among property sources identified. An Intro-ductory section outlines conversions among several metric systems, including SI, and inch--pound units. An appendix summarizes quality requirements for compliance with the Japanese Industrial Standards (JIS) and specifically JIS K1517-1973.

R-13

L. F. Albright and J. J. Martin (University of Michigan), **Thermodynamic Properties of Chlorotrifluoromethane**, *Industrial and Engineering Chemistry*, 44:1-11, 1952 (11 pages, rdb4242)

thermodynamic properties of R-13; thermophysical data

D. E. Diller and L. J. Van Poolen (National Institute of Standards and Technology, NIST), **Measurement of Viscosities of Saturated and Compressed Fluid Chlorotrifluoromethane (R13)**, *Cryogenics*, 29:1063-1066, November 1989 (4 pages with 6 figures and 2 tables, available from JMC as RDB7834)

presents shear viscosity coefficients of saturated and compressed fluid R-13: describes measurements made with a torsional crystal viscometer at -173 to 47 °C (-280 to 116 °F) and pressures up to 35 MPa (5100 psia); presents a correlation to a fluidity-viscosity equation and examines the dependence of viscosity on density, molar volume, and temperature; transport properties; thermophysical data

K. Oguchi, I. Tanashita, K. Watanabe (Keio University, Japan), T. Yamaguchi, and A. Sasayama, **Experimental Study of P-V-T Properties of Fluorocarbon Refrigerant R 13 ($CClF_3$) (Second Report: Experimental Results of the Saturation Pressure and Determination of the Critical Parameters)**, *Bulletin of the Japan Society of Mechanical Engineers* (JSME), 18(126):1456-1464, 1975 (9 pages, rdb7B25)

thermodynamic properties of R-13; thermophysical data

A. M. Shavandrin and S. A. LI, *Izvestiya Vysshikh Uchebnykh Zavedenii Energetika*, 26(8):87-90, 1983 (4 pages in Russian, rdb7B26)

thermodynamic properties of R-13: density, thermophysical data

R-13B1

Y. Higashi, M. Uematsu, and K. Watanabe (Keio University, Japan), **Measurements of the Vapor-Liquid Coexistence Curve and Determination of the Critical Parameters for Refrigerant 13B1**, *Bulletin of the Japan Society of Mechanical Engineers* (JSME), 28(245):2660-2666, 1971 (7 pages, rdb7B27)

thermodynamic properties of R-13B1; thermophysical data

J. J. Martin, L. M. Welshans, C. H. Chou, and G. E. Gryka, **Data and Equations for Some Thermodynamic Properties of Freon-13B1 ($CBrF_3$)**, report on project M777, University of Michigan, Ann Arbor, MI, April 1953 (rdb3914)

thermodynamic properties of R-13B1: equation of state (EOS); thermophysical data

I. I. Perelshtein and Y. P. Aleshin, **Experimental Investigation of the Thermodynamic Properties of Freon-13B1**, *Thermophysical Properties of Matter* *and Substances*, edited by V. A. Rabinovich, Moscow, Russia (then USSR), 4:52-67, 1971 (rdb7B28)

thermodynamic properties of R-13B1; thermophysical data

Thermophysical Properties of Refrigerants (R-13B1, Bromotrifluoromethane), Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, March 1989 (162 pages with 25 figures and 50 tables, in both Japanese and English, rdb0402)

This comprehensive volume summarizes critical, thermodynamic, transport, physical, chemical, compatibility, and other data available on R-13B1. Included are tabular data and/or plots for PVT properties, enthalpy, entropy, isobaric and isochoric specific heat capacity, specific heat ratio, speed of sound, surface tension, viscosity, kinematic viscosity, thermal conductivity, thermal diffusivity, Prandtl number, solubility, refractive index, dielectric constant, volume resistivity, and dielectric strength. An equation of state is presented and compared to other equations and data. Relations also are presented for key equilibrium properties. Data are tabulated for the solubility of R-13B1 in both a naphthenic mineral oil and a synthetic polyglycol lubricant. Limited stability and compatibility data are outlined. Published safety data, including toxicity and flammability, are summarized. The volume contains an extensive list of references as well as discussion of the ranges and differences among property sources identified. An introductory section outlines conversions among several metric systems, including SI, and inch-pound units. An appendix addresses compliance with the Japanese Industrial Standards (JIS), noting that the quality of R-13B1 is not covered; requirements for the quality of R-13B1 as a fire extinguishant, Halon 1301, under an ordinance of the Ministry of Home Affairs are summarized. R-13B1 also is regulated as a "liquified gas" by the Japanese Regulation on High-Pressure Gases.

R-13I1

Y-Y. Duan, L. Shi, M-S. Zhu, and L-Z. Han (Tsinghua University, China), **Surface Tension of Trifluoroiodomethane (CF_3I)**, *Fluid Phase Equillbria*, 154(1):71-77, 4 January 1999 (7 pages with 5 figures and 1 table, RDB9110)

measurements of the surface tension of R-13I1 under vapor-liquid equilibrium (VLE) conditions by the differential capillary rise method (DCRM) for -30 to 71 °C (-22 to 160 °F): presents the apparatus used, raw data, and a correlation for them; also presents analyses of their relation to reduced temperatures (ratio to the critical temperature) and deviations between the fit equations and measurements

Y-Y. Duan, L Shi, L-Z. Han, and M-S. Zhu (Tsinghua University, China), **Viscosity of Saturated Liquid Trifluoroiodomethane from 253 to 383 K**, *Fluid Phase Equilibria*, 162:303-312, 1999 (10 pages with 5 figures and 3 tables, RDB9712)

measurements of the viscosity of R-13I1 under vapor-liquid equilibrium (VLE) conditions using a calibrated capillary viscometer for -20 to 65 °C (-4 to 149 °F): presents the apparatus used, calibration approach, raw data, and a correlation for them

R-14

H. Enokido, T. Shinoda, and Y. Mashiko, **Thermodynamic Properties of Carbon Tetrafluoride from 40 K to its Melting Point**, *Bulletin of the Chem. Society of Japan*, 42(12):3415-3421, 1969 (7 pages, rdb7B20)

thermodynamic properties of R-14; thermophysical data

R. G. Rubio, J. C. G. Calado, P. Clancy, and W. B. Streett, **A Theoretical and Experimental Study of the Equation of State of Tetrafluoromethane**, *Journal of Physical Chemistry*, 89:4637-4646, 1985 (8 pages, rdb7C62)

R-14, thermodynamic properties, thermophysical data, EOS

M. Simon, C. M. Knobler, and A. G. Duncan, **The Vapor Pressure of Tetrafluoromethane from 86 to 146 K**, *Cryogenics*, 7:138-140, 1967 (3 pages, rdb7B22)

R-23, thermodynamic properties from -187 to -125 °C (-305 to -197 °F), thermophysical data

J. H. Smith and E. L. Pace, **The Thermodynamic Properties of Carbon Tetrafluoride from 12 K to its Boiling Point**, *Journal of Physical Chemistry*, 73(12):4232-4236, 1969 (5 pages, rdb7B23)

R-23, thermodynamic properties from -261 °C (-438 °F) to its boiling point, thermophysical data

R-22

D. R. Defibaugh and G. Morrison (National Institute of Standards and Technology, NIST), **Compressed**

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Liquid Densities and Saturation Densities of Chlorodifluoromethane (R22), *Journal of Chemical and Engineering Data*, 37(1):107-110, 1992 (4 pages with 7 figures and 2 tables, RDB4347)

presents density measurements for liquid R-22 for 13 isotherms between -10 and 100 °C (14-212 °F) and 1.0-6.2 MPa (145-900 psia); the measurements were made with a vibrating tube densimeter; the accuracy of the data is estimated as ±0.05% except near the critical point; thermodynamic properties; thermophysical data

D. E. Diller, A. S. Aragon, and A. Laesecke (National Institute of Standards and Technology, NIST), **Measurements of the Viscosities of Saturated and Compressed Liquid Chlorodifluoromethane (R22)**, *International Journal of Refrigeration* (IJR), 16(1):19-22, January 1993, and an unpublished erratum (5 pages with 4 figures, 2 tables; available from JMC as RDB4349)

transport properties of R-22: measurements of the shear viscosity coefficient for -153 to 47 °C (-244 to 116 °F) and pressures up to 30 MPa (4350 psia) with a torsional crystal viscometer; data are correlated to an empirical fluidity-volume equation; paper presents the apparatus, procedures, measured data, and cited correlation [a corrected fluidity-volume equation was obtained from the authors, but not published pending development of a more comprehensive correlation]; thermophysical data

V. Z. Geller, E. M. Karbonov, B. V. Gunchuk, V. Y. Zakhazhevsky, and N. I. Lapardin, **Viscosity Coefficients of Liquified Gases Near the Saturation Curve**, *Gazov Promst*, 3:32 ff, 1976 (in Russian, rdb8320)

transport properties of R-22 and others; viscosity; thermophysical data

J. X. Guo, Z. Y. Zhao, J. M. Yin, and L-C. Tan (Xi'an Jiaotong University, China), **Variable-Volume Apparatus for the Measurements of PVTx Properties of Fluids**, *Preprints of the 11th Symposium on Thermophysical Properties* (Boulder, CO, 23-27 June 1991), American Society of Mechanical Engineers (ASME), New York, NY, 1991; republished in *Fluid Phase Equilibria,* 88(5):151-157, 10 August 1993 (7 pages, rdb8938)

describes a new apparatus for measurement of PVTx properties and tests with R-22: the apparatus entails a variable-volume, sample container to measure pressures a controlled temperatures for continuously-adjustable volumes

A. Kamei, S. W. Beyerlein, and R. T. Jacobsen (University of Idaho, **Application of Nonlinear Regression in the Development of a Wide-Range Formulation for HCFC-22**, *International Journal of Thermophysics,* 16(5):1155-1164, September 1995 (10 pages, rdb7734)

presents an equation of state (EOS) for R-22 for temperatures from the triple point (-157.42 °C, -251.36 °F) to 277 °C (530 °F) at pressures up to 60 MPa (8700 psia) with an accuracy of ±0.1% in density, ±0.3% in speed of sound, and ±1.0% in isobaric heat capacity; thermodynamic properties, thermophysical data

A. Kamei, S. W. Beyerlein, and E. W. Lemmon (University of Idaho), **Fundamental Equation for Chlorodifluoromethane (R-22)**, *Preprints of the 11th Symposium on Thermophysical Properties* (Boulder, CO, 23-27 June 1991), American Society of Mechanical Engineers (ASME), New York, NY, 1991; republished in *Fluid Phase Equilibria,* 80(4):71-85, 30 November 1992 (12 pages, RDB3915)

presents a fundamental equation (FEQ) based on Helmholtz energy for R-22; this equation of state (EOS) is applicable for -73 to 277 °C (-100 to 530 °F) for pressures up to 60 MPa (8700 psia); temperatures are given on the new International Temperature Scale of 1990 (ITS-90); the EOS development incorporated new pressure-density-temperature data and speed of sound data in the liquid region; also presents new ancillary functions for the vapor pressure, saturated liquid density, saturated vapor density, and ideal gas heat capacity; the accuracy of the new formulation is estimated to be ±0.2% in density, ±1.0% in heat capacities, and ±0.5% in sound velocity; thermodynamic properties; thermophysical data

A. Kamei, S. W. Beyerlein, R. T. Jacobsen, and K. R. Den Braven, **A New Interim Thermodynamic Property Formulation for Chlorodifluoromethane (R-22)**, *Symposium on Global Climate Change and Refrigerant Properties* (AIChE Spring National Meeting, Orlando, FL, 18-22 March 1990), American Institute of Chemical Engineers (AIChE), New York, NY, 1990 (rdb9114)

presents a fundamental equation (FEQ) based on Helmholtz energy for R-22; equation of state (EOS); thermodynamic properties; thermophysical data

A. V. Kletskii and S. T. Butierskaya, **Coefficient of Dynamic Viscosity of Liquid Freon 22**, *Kolloidnyi Tekhnika* [Refrigeration Technology], 6:31 ff, 1973 (in Russian, rdb8319)

transport properties of R-22; viscosity; thermophysical data

A. V. Kletskii and V. Krivaya, **Uprolosti Freona-22**, *Inzhenerno-Fizicheskii Zhurnal* [Journal of Engineering Physics], Minsk, Belarus (then USSR), 7(4):40-43, 1964 (4 pages probably in Russian, rdb-7C09)

thermodynamic properties of R-22: vapor pressure; thermophysical data

R. Kohlen, **Das Fluide Zustandsgebiet von R-22: Berechnung, Korrelationen** [The Vapor-Phase Region of R-22: Calculations, Correlations], report series 19 number 14, Verein Deutscher Ingenieure (VDI) [Association of German Engineers] Verlag, Dusseldorf, Germany, 1987 (in German, rdb5492)

R-22, thermodynamic properties, thermophysical data

R. Kohlen, H. Kratzke, and S. Müller, **Thermodynamic Properties of Saturated and Compressed Liquid Difluorochloromethane**, *Journal of Chemical Thermodynamics*, 17:1141-1151, 1985 (11 pages, rdb4142)

thermodynamic properties of R-22, thermophysical data

B. Kruppa and J. Straub (Technische Universität München, TUM, Germany), **Thermal Diffusivity of Refrigerants**, *Thermophysical Properties of Pure Substances and Mixtures for Refrigeration* (proceedings of the meeting of IIR Commission B1, Herzlia, Israel, March 1990), International Institute of Refrigeration (IIR), Paris, France, 69-75, 1990 (7 pages with 4 figures and 2 tables, RDB5623)

R-22, thermal diffusivity, transport data, photon correlation spectroscopy; presents results for R-22, but indicates that measurements also have been made for R-13, R-13B1, R-23, R-744, R-744A, R-7146, R-23/7146, and R-7146/1381

I. R. Martín-Dominguez and T. W. McDonald (University of Windsor, Canada), **Correlations for Some Saturated Thermodynamic and Transport Properties of Refrigerant R-22**, technical paper 3655, *Transactions* (Winter Meeting, Chicago, IL, January 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(1):344-348, 1993 (5 pages with 8 figures and 8 tables, RDB8944)

presents correlations obtained by least squares, linear regression for the saturation temperature and pressure, heat of vaporization, vaporization specific volume, density of saturated vapor, saturated liquid dynamic viscosity, saturated vapor dynamic viscosity, and thermal conductivity of saturated liquid for -90 to 95 °C (-130 to 203 °F) based on published property data: graphically compares the equations with the published data; figures show the fitted curves, data points, and the resulting errors

K. Oguchi, H. Sagara, I. Matsushita, K. Watanabe (Keio University, Japan), and I. Tanashita, **Experimental Study of PVT Relations for Fluorinated Hydrocarbon R22**, *Nippon Kikai Gakkai Ronbunshu* (Transactions of the Japan Society of Mechanical Engineers, JSME), JSME, Tokyo, Japan, B45(398):1522-1528, 1979 (7 pages in Japanese, rdb7C36)

thermodynamic properties of R-22; thermophysical data

K. Oguchi, Y. Matsushita, H. Sagara, K. Watanabe, I. Matsushita, and I. Tanishita (Keio University, Japan), and I. Tanashita, **Pressure-Volume-Temperature Properties of Chlorodifluoromethane (R22) in Liquid and Gaseous States**, *Proceedings of the XIVth International Congress of Refrigeration* (Moscow, USSR), International Institute of Refrigeration (IIR), Paris, France, 11:55-61, 1978 (7 pages, rdb9117)

thermodynamic properties of R-22; thermophysical data

K. Stephan and J. Biermann (Universität Stuttgart, Germany), **Thermal Diffusivity Measurement of Refrigerant 22 at Low Pressures Using the Photoacoustic Effect**, *Proceedings of the 1992 International Refrigeration Conference - Energy Efficiency and New Refrigerants*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 1:149-156, July 1992 (8 pages with 5 figures and 2 tables, RDB2716)

thermodynamic properties of R-22; thermophysical data

M. Uematsu and H. Fukuizumi, **Density, Isothermal Compressibility, and the Volume Expansion Coefficient of Liquid Chlorodifluoromethane for Temperatures of 310-400 K and Pressures up to 10 MPa**, *Journal of Chemical and Engineering Data*, 36:91-93, 1991 (3 pages, rdb8241)

thermodynamic properties of R-22 for 37-127 °C (98-260 °F) and pressures up to 10 MPa (1450 psia); thermophysical data

W. Wagner, V. Marx, and A. Pruß, **A New Equation of State for Chlorodifluoromethane (R22) Covering the Entire Fluid Region from 116 K to 550 K at Pressures up to 200 MPa**, *International Journal of Refrigeration* (IJR), 16(6):373-388, 1993 (6 pages, rdb8265)

thermodynamic properties of R-22: equation of state (EOS) for -157 to 277 °C (-251 to 530 °F) and pressures up to 200 MPa (29,000 psia); thermophysical data

Thermophysical Properties of Refrigerants (R22, Chlorodifluoromethane), Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tok-

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yo, Japan, November 1975 with errata dated 1986 (132 pages with 21 figures and 38 tables plus 16 page errata, in both Japanese and English, rdb0403)

This comprehensive volume summarizes critical, thermodynamic, transport, physical, chemical, compatibility, and other data available on R22. Included are tabular data and/or plots for PVT properties, enthalpy, entropy, isobaric and isochoric specific heat capacity, specific heat ratio, speed of sound, surface tension, viscosity, kinematic viscosity, thermal conductivity, thermal diffusivity, Prandtl number, solubility, refractive index, dielectric constant, volume resistivity, and dielectric strength. A section on physical and chemical provides tabular data on the solubility of R-22 in water, miscibility diagrams for naphthenic and paraffinic mineral oils in R-22, and plots of the solubility in naphthenic mineral oil. It also identifies the decomposition products of R-22 in several heat sources and indicates the hydrolysis rate of R-22 in water alone and with several metal catalysts. The effects of R-22 on plastics are summarized, including polytetrafluoroethylene (PTFE), tetrafluoroethylene-hexafluoropropylene copolymer, poly(1-chloro-1,2,2-trifluoroethylene), polyvinyl alcohol, polyethylene, polyvinylchloride (PVC), polyvinylidene chloride, nylon resin, acrylic resin (polymethacrylate), polystyrene, phenolic resin, epoxy resin, acetal resin, cellulose acetate, cellulose nitrate, and acryl fiber. Linear swell data are tabulated for neat R-12, oil, and a 50/50 mixture with elastomers including Buna™ N, Buna™ S, neoprene W (type GN), butyl rubber, and natural rubber. The maximum temperature limit is provided for R-22 with several enamel (varnish) types, including acrylic, polyvinyl formal, isocyanate modified polyvinyl formal, polyamide imide, polyester imide, and polyimide. Published safety data, including toxicity and flammability, are summarized and explosion limit curves are provided for air mixtures. An equation of state is presented and compared to other equations and data. Relations also are presented for key equilibrium properties. Published safety data, including toxicity and flammability, are summarized. The volume contains an extensive list of references as well as discussion of the ranges and differences among property sources identified. An introductory section outlines conversions among several metric systems, including SI, and inch-pound units. An appendix summarizes quality requirements for compliance with the Japanese Industrial Standards (JIS) and specifically JIS K1519-1973.

R-23

A. G. Aizpiri, A. Rey, J. Dávila, R. G. Rubio, J. A. Zollweg, and W. B. Streett**, Experimental and Theoretical Study of the Equation of State of CHF_3 in the Near-Critical Region,** *Journal of Physical Chemistry*, 95:3351-3357, 1991 (7 pages, rdb4A38)

thermodynamic properties of R-23, thermophysical data

J. L. Belzile, S. Kaliaguine, and R. S. Ramalho, **PVT Study of Trifluoromethane by the Burnett Method**, *Canadian Journal of Chemical Engineering*, 54:425-431, 1976 (7 pages, rdb4B28)

R-23, thermodynamic properties, thermophysical data

R. Döring and H. J. Löffler (Technische Universität Berlin, Germany), **Thermodynamische Eigenschaften von Trifluormethan (R23)** [Thermodynamic Properties of Trifluoromethane (R-23)], *Kältetechnik-Klimatisierung*, 20:342-348, 1968 (7 pages, in German, rdb4307)

thermophysical data

N. V. Godvinskaya and V. F. Lysenkov, **Experimental Study of Isochoric Heat Capacity of Freon-23 in a Critical Region**, *Inzhenerno-Fizicheskii Zhurnal*, 60(6):1037 ff, June 1991 (in Russian, rdb8959)

thermodynamic properties of R-23 measured with an adiabatic calorimeter: describes measurements of the isochoric heat capacity obtained on 418.8 and 509.3 kg/m^3 (26.1 and 31.8 lb/ft^3 isochores with an estimated accuracy of 1-2%; thermophysical data

K. Hori, S. Okazaki, M. Uematsu, and K. Watanabe (Keio University, Japan), **An Experimental Study of Thermodynamic Properties of Trifluoromethane**, *Proceedings of the Eighth Thermophysical Properties Symposium* (Gaithersburg, MD, 15-18 June 1981), edited by J. V. Sengers, American Society of Mechanical Engineers (ASME), New York, NY, 2:380-386, 1982 (7 pages, rdb4309)

thermodynamic properties of R-23; thermophysical data

Y. C. Hou and J. J. Martin, **Physical and Thermodynamic Properties of Trifluoromethane**, *AIChE Journal*, 5(1):125-129, 1959 (5 pages, rdb3916)

R-23, equation of state (EOS), thermophysical data

M. Hloucha and U. K. Deiters, **Monte Carlo Study of the Thermodynamic Properties and the Static Dielectric Constant of Liquid Trifluoromethane**, *Fluid Phase Equilibria*, 149(1-2):41-56, August 1998 (16 pages, rdb8C29) thermodynamic properties of R-23; thermophysical data

L. A. Kryukov, **Determination of Freon-23 Density at Room Temperatures at Near Atmospheric Pressures**, *Tr. Mosk. Energ. Inst*, 104:24-25, 1972 (2 pages in Russian, rdb4B29)

thermodynamic properties of R-23; thermophysical data

V. F. Lysenkov and P. V. Popov, **Equation of Phase Equilibrium Line of Freon-23 Taking into Account Specific Features of a Critical Region**, *Inzhenerno-Fizicheskii Zhurnal,* 60(3):501 ff, March 1991 (in Russian, rdb8960)

thermodynamic properties of R-23; presents equations to determine the saturated vapor pressure and the saturated liquid and vapor densities; proposes property equations for relative pressure and density near the triple point; thermophysical data

A. Popowicz, T. Oi, J. Shulman, and T. Ishida (State University of New York), **Vapor Pressure Isotope Effects in Liquid Fluoroform**, *Journal of Chemical Physics*, 76(7):3732-3743, 1 April 1982 (12 pages with 6 figures and 7 tables, rdb4143)

thermodynamic properties of R-23; thermophysical data

D. S. Rasskazov, E. K. Petrov, G. A. Spiridonov, and E. R. Ushmaikin, **Investigation of the p,v,t-Dependence of Freon-23**, *Teplofizicheskie Svoistva Veshchestv i Materialov* [Thermophysical Properties of Substances and Materials], Izdatel'stvo Standartov, Moscow, Russia, 8:4-26, 1975 (23 pages in Russian, rdb4B30)

thermodynamic properties of R-23: PVT; thermophysical data

D. S. Rasskazov, E. K. Petrov, and L. A. Kryukov, **Experimental Investigation of the Caloric Properties of Freon-23**, *Teplofizicheskie Svoistva Veshchestv i Materialov* [Thermophysical Properties of Substances and Materials], Izdatel'stvo Standartov, Moscow, Russia, 8:100-107, 1975 (8 pages, in Russian, rdb4B31)

thermodynamic properties of R-23; thermophysical data

D. S. Rasskazov, U. M. Babikov, and N. Y. Filatov, **Experimental Study of Viscosity of Freon-23**, *Teplofizicheskie Svoistva Veshchestv i Materialov* [Thermophysical Properties of Substances and Materials], Izdatel'stvo Standartov, Moscow, Russia, 8:142-147, 1975 (6 pages, in Russian, rdb4B32)

R-23, transport properties, thermophysical data

D. S. Rasskazov, E. K. Petrov, and E. R. Ushmaikin, **Experimental Study of Density of Freon-23 in the Liquid Phase**, *Tr. Mosk. Energ. Inst*, 234:52-57, 1975 (6 pages in Russian, rdb4B33)

thermodynamic properties of R-23; thermophysical data

D. S. Rasskazov and L. A. Kryukov, **Properties of Gaseous Freon-23 at Subcritical Pressures**, *Tr. Mosk. Energ. Inst*, 179:108-112, 1974 (5 pages in Russian, rdb4B34)

thermodynamic properties of R-23; thermophysical data

R. G. Rubio, J. A. Zollweg, and W. B. Streett, **A p-V-T Surface for Trifiuoromethane**, *Berichte der Bunsengesellschaft für Physikalische Chemie,* 93:791-800, 1989 (10 pages, rdb4316)

R-23, thermodynamic properties, thermophysical data, PVT

A. M. Shavandrin, T. Y. Rasskazova, and Y. R. Chaskin, **Study of the Temperature-Density Parameters of the Boundary Curve of Fluorochemical F-23 by the Method of Quasistatic Thermograms**, *Tr. Khim. TeknoL*, 4:100-104, 1975 (5 pages in Russian, rdb7C41)

R-23, density, thermodynamic properties, thermophysical data

A. Takanuma, M. Uematsu, and K. Watanabe (Keio University, Japan), **Measurements of the Isobaric Specific Heat Capacity and Formulation of an Equation of State for Refrigerant 23 in the Gaseous Region**, *Nippon Reito Kyokai Ronbunshu* [Transactions of the JAR], Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 2(2):61-68, 1985 (8 pages, rdb4B35)

R-23, thermodynamic properties, thermophysical data

N. I. Timenshenko, E. P. Kholodov, and A. L. Yamnov, **Refractive Index, Polarizability, and Density of Freon-23**, *Teplofizicheskie Svoistva Veshchestv i Materialov* [Thermophysical Properties of Substances and Materials], Izdatel'stvo Standartov, Moscow, Russia, 8:17-26, 1975 (10 pages in Russian, rdb4B36)

R-23, transport properties, thermophysical data

R. H. Valentine, G. E. Brodale, and W. F. Giauque, **Trifluoromethane: Entropy, Low Temperature Heat Capacity, Heats of Fusion and Vaporization, and Vapor Pressure**, *Journal of Physical Chemistry*, 66:392-395, 1962 (4 pages, rdb4321)

R-23, thermodynamic properties, thermophysical data

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W. Wagner, **Thermodynamische Eigenschaften von Trifluormethan** [Thermodynamic Properties of Trifluoromethane], *Kältetechnik-Klimatisierung,* 20(8):238-240, 1968 (3 pages in German, rdb4322)

R-23, thermophysical data

Thermophysical Properties of R-23, research project 997-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, September 1997 - August 1998 (ASH0997)

The research will develop thermodynamic and transport properties and equations for R-23. The results will be presented as a pamphlet summarizing the thermophysical properties in tabular, chart and equation form. The contractor for the work is the University of Idaho led by S. G. Penoncello; it is sponsored by ASHRAE Technical Committee 3.1, *Refrigerants and Brines.*

R-32

Y. Chernyak (University of Delaware, USA), P. V. Zhelezny (Odessa State Academy of Refrigeration, Ukraine), and M. E. Paulaitis (University of Delaware, USA), **Thermodynamic Properties of Difluoromethane on the Saturation Curve**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 435-440, July 1996 (6 pages with 4 figures and 5 tables, RDB6C21)

data source citations and data correlations for the saturated vapor pressure and for the saturated liquid and vapor densities of R-32; listing of data and source citations for critical parameters (temperature, density, and pressure) for R-32; recommended critical properties and coefficients to apply the equations presented, to predict the thermodynamic properties of R-32, over a wide temperature range and in the vicinity of the critical point

D. R. Defibaugh, G. Morrison, and L. A. Weber (National Institute of Standards and Technology, NIST), **Thermodynamic Properties of Difluoromethane**, *Journal of Chemical and Engineering Data,* 38(2):333-340, April 1994 (8 pages with 5 figures and 10 tables, RDB4348)

thermodyanmic properties of R-32: describes measurements of the pressure-volume-temperature (PVT) behavior using a vibrating-tube densimeter and a Burnett isochoric apparatus; correlations with a virial equation of state (EOS) and an abbreviated form of a Benedict-Webb-Rubin (MBWR) EOS; provides tabular data for the saturated liquid and vapor states

Y-Y. Duan, H-W. Xiang, L Shi, et al. (Tsinghua University, China), **A New Equation of State of Difluoromethane (HFC-32) over the Entire Region**, *Qinghua Daxue Xuebao* [Journal of Tsinghua University], Beijing, China 38(5):, 1998 (rdb8C16)

presents an equation of state (EOS) for R-32; thermodynamic properties, thermophysical data

Y-Y. Duan, H-W. Xiang, L. Shi, et al. (Tsinghua University, China), **Thermodynamic Properties of Difluoromethane (HFC-32)**, *Journal of Engineering Thermodynamics*, 19(2):137 ff, 1998 (rdb8C18)

thermodynamic properties of R-32; thermophysical data

Y-D. Fu, L-Z. Han, and M-S. Zhu (Tsinghua University, China), **PVT Properties, Vapor Pressures, and Critical Parameters of HFC-32,** *Fluid Phase Equilibria,* 111(2):273-286, October 1995 (14 pages with 5 figures and 9 tables, RDB7735)

summarizes measurements of pressure-volume-temperature (PVT) data for R-32 in the vapor phase using a three-chamber Burnett apparatus along fourteen isotherms for temperatures from -30 to 100 °C (-22 to 212 °F) and pressures from 0.07-5.7 MPa (10-827 °F); also summarizes measurements of vapor pressure for the temperature range from -40 to 78 °C (-40 to 172 °F); demonstrates agreement of the data to an equation of state (EOS) developed by Piao et al. with an RMS deviation of 0.17% and 0.063%, respectively, for the two sets; presents a new vapor pressure equation for R-32 based on these data and those from other investigators; presents new determinations of the critical temperature, density, and pressure for R-32 as 78.145 ±0.010 °C (172.661 ± 0.006 °F), 425 ±3 kg/m^3 (26.53 ±0.02 lb/ft^3), and 5.785 ±0.002 MPa (839 ±0.3 psia), respectively, based on visual observation of the disappearance of the meniscus in an optical cell

Y-D. Fu, L-Z. Han, and M-S. Zhu (Tsinghua University, China), **PVT Properties of Difluoromethane (HFC-32)**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:201-206, 1995 (6 pages with 4 figures and 3 tables, rdb7805)

thermodynamic properties of R-32; thermophysical data

Y. Higashi, H. Imaizumi, and S. Usuba (Iwaki Meisei University, Japan), **Measurement of the Critical Parameters for HFC-32**, *Proceedings of the 13th Japan Symposium on Thermophysical Properties,* Akita, Japan, 65-68, 1992 (4 pages in Japanese, rdb4B21)

thermodynamic properties of R-32; thermophysical data

T. Hozumi, H. Sato, and K. Watanabe (Keio University, Japan), **Speed of Sound in Gaseous Difluoromethane,** *Journal of Chemical and Engineering Data,* 39:493-495, 1994 (3 pages, rdb8952)

properties of R-32; thermophysical data

H. Kubota, T. Sotani, and Y. Kunimoto, **Isobaric Specific Heat Capacity of Difluoromethane at Pressure up to 0.5 MPa**, *Fluid Phase Equilibria,* 104:413-419, 1995 (7 pages, rdb8955)

properties of R-32; thermophysical data

S. Kuwabara, J. Tatoh, H. Sato, and K. Watanabe (Keio University, Japan), **Critical Parameters and Vapor-Liquid Coexistence Curve in the Critical Region for HFC-32**, *Proceedings of the 13th Japan Symposium on Thermophysical Properties,* Akita, Japan, 69-72, 1992 (4 pages, rdb4B23)

thermodynamic properties of R-32; thermophysical data

A. P. Kuznetov and L. V. Los, **Thermophysical Properties of Freons - Calculation of Thermodynamic Properties of Difluoromethane (Freon 32)**, *Kolloidnyi Tekh. Tekhnol.,* 12:40-43, 1985 (4 pages in Russian, RDB8953)

thermodynamic properties of R-32; thermophysical data

M. Lisal and V. Vacek (Czech Technical University, Czechoslovakia), **Molecular Dynamics Studies for the New Refrigerant HFC-32 with Site-Site Effective Pair Potential**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:383-390, 1995 (8 pages with 5 figures and 1 table, rdb7828)

R-32: thermodynamic, structural, and dynamic properties, PVT data, heat of vaporization, thermophysical data

P. F. Malbrunot, P. A. Meunier, G. M. Scatena (Laboratoire des Hauts Pressions, France), W. H. Mears, K. P. Murphy, and J. V. Sinka (AlliedSignal Incorporated, then Allied Chemical Corporation), **Pressure-Volume-Temperature Behavior of Difluoromethane**, *Journal of Chemical and Engineering Data,* 13(1):16-21, January 1968 (6 pages with 3 figures and 7 tables, RDB2310)

The pressure-volume-temperature (PVT) properties of R-32 are correlated using the Martin-Hou equation of state to within ±0.94% standard deviation over the experimental ranges: 25-200 °C (77-392 °F), 0.8-20 MPa (120-2900 psia), and 47-1.8 cc/g (0.75-0.03 cf/lb). Vapor pressures have been determined from -83 °C (-117 °F) to 78.4 °C (173 °F), the measured critical temperature. Using liquid densities measured between -25 and 78 °C (-13 and 172 °F) and densities of saturated vapor computed from the Martin-Hou equation, a rectilinear diameter line has been developed. The critical pressure and density are 5.830 MPa (846 psia) and 430 kg/m^3 (26.8 lb/cf), respectively.

C. A. Nieto de Castro, F. J. V. Santos (Universidade de Lisboa, Portugal), and U. V. Mardolcar (Instituto Superior Tecnico, Portugal), **The Dielectric Constant of Liquid HFC-32**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:436-441, 1995 (6 pages with 2 figures and 2 tables, rdb7843)

R-32, physical properties, thermophysical data, measurements with an impedance analyzer

A. Nishimura, Z-Y. Qian, H. Sato, and K. Watanabe (Keio University, Japan), **Thermodynamic Properties of HFC-32 at the Gaseous Phase and Saturated States**, *Proceedings of the 13th Japan Symposium on Thermophysical Properties*, Akita, Japan, 57-60, 1992 (4 pages, rdb4B24)

thermodynamic properties of R-32; thermophysical data

C-C. Piao, M. Noguchi (Daikin Industries, Limited, Japan), H. Sato, and K. Watanabe (Keio University, Japan), **Thermodynamic Properties of a New Working Fluid, HFC-32**, *Proceedings of the 1993 Annual Conference,* Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 13-16, 1993 (4 pages with 6 figures and 3 tables in Japanese, RDB4873)

thermodynamic properties of R-32: modified Benedict-Webb-Rubin (BWR) equation of state (EOS); thermophysical data

Z-Y. Qian, A. Nishimura, H. Sato, and K. Watanabe (Keio University, Japan), **Compressibility Factors and Virial Coefficients of Difluoromethane (HFC-32) Determined by the Burnett Method,** *JSME International Journal* (*series II: Fluids Engineering, Heat Transfer, Power, Combustion, and Thermophysical Properties),* Japan Society of Mechanical Engineers (JSME), Tokyo, Japan, 36:665-670, 1993 (6 pages in English, available from ASME in the Americas and from Maruzen Company, Limited, elsewhere, rdb6448)

please see page 6 for ordering information

thermodynamic properties of R-32; thermophysical data

Z-Y. Qian, H. Matsunobe, H. Sato, and K. Watanabe (Keio University, Japan), **Thermodynamic Property Measurements for Difluoromethane (HFC-32) by a Burnett Method,** paper B103, *Proceedings of the Twelfth Japan Symposium on Thermophysical Properties*, 73-76, 1991 (4 pages with 8 figures, RDB2428)

This paper summarizes measurements of vapor pressures of R-32 at temperatures of 300-330 K (80-134 °F) and compressibility factors for 300-350 K (80-170 °F) and 0.15-4.3 MPa (22-624 psia). The experimental apparatus used, based on a Burnett method, is briefly described. Second and third virial coefficients for property calculations are presented. A systematic error, related to an adsorption effect in the Burnett experimental procedure, and a correction are discussed.

T. Sato, H. Sato, and K. Watanabe (Keio University, Japan), **PVT Property Measurements of Difluoromethane**, *Journal of Chemical and Engineering Data*, 39(4):851-854, 1994 (4 pages, rdb7859)

thermodynamic properties of R-32; thermophysical data

T. Sato, H. Sato, and K. Watanabe (Keio University, Japan), **A Study of PVT Properties of HFC-32**, *Proceedings of the 13th Japan Symposium on Thermophysical Properties*, Akita, Japan, 49-52, 1992 (rdb4A43)

thermodynamic properties of R-32; thermophysical data

L. Shi, M-S. Zhu, L-Z. Han, Y-Y. Duan, L-Q. Sun, and Y-D. Fu (Tsinghua University, China), **Thermophysical Properties of Difluoromethane (HFC-32)**, *Science in China*, China, series E, 41(4):435-442, August 1998 (8 pages with 7 figures and 4 tables, RDB8C14)

thermodynamic properties of R-32; thermophysical data

L-Q. Sun, Y-Y. Duan, L. Shi, M-S. Zhu, and L-Z. Han (Tsinghua University, China), **Speed of Sound and Ideal-Gas Heat Capacity at Constant Pressure of Gaseous Difluoromethane**, *Journal of Chemical and Engineering Data*, 42(4):795-799, 1997 (5 pages with 8 figures and 2 tables, RDB8C17)

measurements of the speed of sound in R-32 for 0-60 °C (32-140 °F) and 48-390 kPa (7-57 psia) with a cylindrical, variable-path, acoustic interferometer; describes determination of the ideal gas heat capacity at constant pressure and the second virial coefficients form those data; compares the results those calculated form to data published from other studies and to speed of sound measurements; estimates the uncertainty to be less than ±1%; describes the apparatus and tabulates the measured data

R. Tillner-Roth (Universität Hannover, Germany) and A. Yokozeki (DuPont Chemicals), **An International Standard Equation of State for Difluoroethane (R-32) for Temperatures from the Triple Point at 136.34 K to 435 K and Pressures up to 70 MPa**, *Journal of Physical and Chemical Reference Data*, 26(6):1273-1328, 1997 (56 pages with 20 figures and 17 tables, available as reprint 532 from the American Chemical Society, ACS, RDB8970)

fundamental equation of state (EOS) for the Helmholtz free energy of R-32 from the triple point at -136.81 °C (-214.26 °F) to 162 °C (323 °F) and pressures up to 70 MPa (10,200 psia): EOS is based on available measurements of pressure-density-temperature relations, speed of sound, heat capacity, and vapor pressure; compares the 19-coefficient EOS to equations reported in other studies; presents new values for the isobaric heat capacity of the ideal gas; thermodynamic properties; thermophysical data

H-X. Wang, Z. Li, Y-T. Ma, and C-R. Lu, **Experimental Research on Vapor Pressure and Critical Parameters of HFC-32**, *Engineering, Thermodynamics, and Utilization of Energy* (proceedings of the conference, Jiangxi, China, 1993), IV:104-109, 1993 (6 pages in Chinese, rdb8947)

thermodynamic properties of R-32; thermophysical data

L. A. Weber and A. R. H. Goodwin (National Institute of Standards and Technology, NIST), **Ebulliometric Measurement of the Vapor Pressure of Difluoromethane**, *Journal of Chemical and Engineering Data,* 38(2):254-256, 1993 (3 pages with 2 figures and 2 tables, available from JMC as RDB-4910)

This paper presents measured vapor pressure data for R-32 at relatively low temperatures and pressures, between -65 and -36 °C (-85 and -33 °F). It describes a comparative ebulliometer used for the measurements. The paper shows and tabulates deviations of the measured data from fits to an Antoine equation and, combined with data from other researchers, to a Wagner equation. It compares the findings to those published by others. The results offer a means to calculate the vapor pressure of R-32 from -83 °C to the critical temperature, 78.21 °C (-118 to 172.78 °F). The paper then presents calculated thermodynamic properties, including liquid and vapor pressure, density, enthalpy, entropy, and specific heat at low temperatures, from -73 to

-23 °C (-100 to -10 °F). It also presents estimates of the second virial coefficients for R-32.

M. Yomo, H. Sato, and K. Watanabe (Keio University, Japan), **Measurements of Isobaric Heat Capacity for Liquid Difluoromethane** (HFC-32), *High Temperatures - High Pressures*, 26:267 ff, 1994 (rdb8971)

thermophysical properties of R-32

M-S. Zhu and C-X. Lu (Tsinghua University, China), **Surface Tension of Difiuoromethane**, *Journal of Chemical and Engineering Data,* 39(2):205-206, 1994 (2 pages with 3 figures and 1 table, RDB8C19)

measurements of the surface tension of R-32 using the differential capillary method for -5.2 to 61.1 °C (23-142 °F); correlation with a van der Waals equation; tabulates the measured and predicted data; concludes that most of the measured data fit the correlation with deviations of less than 3%

M-S. Zhu, J. Li, and B-X. Wang (Tsinghua University, China), **Vapor Pressure of Difluoromethane (HFC-32)**, *International Journal of Thermophysics,* 14:1221 ff, 1993 (rdb8C15)

thermodynamic properties of R-32; thermophysical data

M-S. Zhu, J. Li, and C-X. Lu (Tsinghua University, China), **Experimental Research on Vapor Pressure and Surface Tension of HFC-32**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC), Alliance for Responsible CFC Policy, Arlington, VA, 54-60, October 1993 (7 pages with 6 figures and 3 tables, RDB3A26)

thermodynamic properties of R-32; thermophysical data

Genetron(R) HFC-32, technical bulletin 525-642, AlliedSignal Incorporated, Morristown, NJ, April 1991 (4 pages with 3 tables, RDB4105)

This bulletin provides physical property, comparative performance, and thermodynamic data on R-32, difluoromethane, in inch-pound (IP) units. It summarizes physical properties including the chemical formula, molecular weight, atmospheric boiling point, corresponding heat of vaporization, critical parameters (temperature, pressure, and density), and flammability. It also indicates the liquid density and specific heats of the liquid and vapor at 26.7 °C (80 °F) as well as the ozone depletion potential (ODP) and estimated global warming potential (GWP). It then presents a performance comparison for R-12, R-22, R-32, and R-502. The report tabulates thermodynamic properties (pressure, liquid density, vapor volume, liquid and vapor enthalpy and entropy, and latent heat of vaporization) for -40 to 60 °C (-40 to 140 °F). Formulae are provided to calculate thermodynamic properties including vapor pressure, liquid density, and ideal gas heat capacity correlations. A Martin-Hou equation of state also is presented. AlliedSignal's product name for R-32 is Genetron® 32.

Thermodynamic Properties of Klea® 32, British Units, bulletin 620250270, ICI Klea, Wilmington, DE, July 1993 (56 pages with 2 tables, limited copies available from JMC as RDB4107)

This bulletin provides detailed thermodynamic properties for saturated and superheated R-32 in inch-pound (IP) units of measure. It comprises two tables. The first presents saturation properties by temperature (°F and °R) for -84 to 78 °C (-120 to 172 °F) and at the critical point, 78.35 °C (173.03 °F). The tabular data include absolute and gauge pressure; liquid and vapor specific volume, density, enthalpy, and entropy; and the latent heat of vaporization. The second table provides volume, enthalpy, and entropy data for superheated vapor at constant pressure. The data span the range of 14-5170 kPa (2-750 psia) to temperatures as high as 114 °C (238 °F). ICI's product name for R-32 is Klea® 32.

Thermodynamic Properties of Klea 32, SI Units, bulletin CP/30473/1Ed/152/1192, ICI Chemicals and Polymers Limited, Runcorn, Cheshire, UK, November 1992 (60 pages with 2 tables, RDB6B28)

This bulletin provides detailed thermodynamic properties for saturated and superheated R-32 in metric (SI) units of measure. It comprises two tables. The first presents saturation properties by temperature (°C and K) for -80 to 78 °C (-112 to 172 °F) and at the critical point, 78.35 °C (173.03 °F). The tabular data include absolute pressure; liquid and vapor specific volume, density, enthalpy, and entropy; and the latent heat of vaporization. The second table provides volume, enthalpy, and entropy data for superheated vapor at constant pressure. The data span the range of 20-5500 kPa (3-800 psia) to temperatures as high as 198 °C (388 °F). ICI's product name for R-32 is Klea® 32.

R-50 (Methane)

S. Angus, B. Armstrong, and K. M. de Reuck, **International Thermodynamic Tables of the Fluid State - 5: Methane**, Chemical Data Series Number 16, International Union of Pure and Applied Chem-

please see page 6 for ordering information

istry (IUPAC), Pergammon Press, Oxford, UK, 1978 (rdb3943)

R-50, equation of state (EOS), thermodynamic properties, thermophysical data

D. G. Friend, J. F. Ely, and H. Ingham (National Institute of Standards and Technology, NIST), **Thermophysical Properties of Methane,** *Journal of Physical and Chemical Reference Data*, 18:583-638, 1989 (56 pages, rdb4223)

R-50, thermodynamic properties

G. Händel, R. Kleinrahm, and W. Wagner, **Measurements of the Pressure-Density-Temperature Relation of Methane in the Homogeneous Gas and Liquid Regions in the Temperature Range from 100 K to 260 K and at Pressures up to 8 MPa,** *Journal of Chemical Thermodynamics,* 24:685 ff, 1991 (rdb8C40)

thermodynamic properties of R-50 (methane) for -173 to -13 °C (-280 to 8 °F) and pressures up to 8 MPa (1160 psia): thermophysical data

R. Kleinrahm, W. Duschek, W. Wagner, and M. Jaeschke, **Measurement and Correlation of the Pressure-Density-Temperature Relation of Methane in the Temperature Range from 273.15 K to 323.15 K and at Pressures up to 8 MPa,** *Journal of Chemical Thermodynamics*, 20:621 ff, 1987 (rdb-8C41)

thermodynamic properties of R-50 (methane) for 0-50 °C (32-122 °F) and pressures up to 8 MPa (1160 psia): thermophysical data

R. Kleinrahm and W. Wagner, **Measurement and Correlation of the Equilibrium Liquid and Vapor Densities and the Vapor Pressure Along the Coexistence Curve of Methane,** *Journal of Chemical Thermodynamics,* 18:739 ff, 1986 (rdb3125)

R-50, thermodynamic properties, thermophysical data

U. Setzmann and W. Wagner, **A New Equation of State and Tables of Thermodynamic Properties for Methane Covering the Range from the Melting Line to 625 K at Pressures up to 1000 MPa,** *Journal of Physical and Chemical Reference Data*, 20(6):1061-1155, 1991 (95 pages, rdb7B32)

R-50 (methane): thermodynamic properties from the freezing line to 352 °C (653 °F) and 1000 MPa (145,000 psia), thermophysical data, equation of state (EOS)

R-113

V. Z. Geller, **Study of the Thermophysical Properties of Freon 113,** *Teploflzicheskie Svoistva Veshchestv i Materialov* [Thermophysical Properties of Substances and Materials], Izdatel'stvo Standartov, Moscow, Russia, 6:135-154, 1973 (20 pages in Russian, rdb7C49)

R-113, density, thermodynamic properties, thermophysical data

H. Hiroaka and J. H. Hildebrand, **Solubility Relations of the Isometric Trichlorotrifluoroethanes,** *Journal of Physical Chemistry*, 67:916-918, 1963 (3 pages, rdb7C39)

R-113 and R-113a, vapor pressure, thermodynamic properties, thermophysical data

M. J. Mastroianni, R. F. Stahl, and P. N. Sheldon, **Physical and Thermodynamic Properties of 1,1,2-Trifluorotrichloroethane (R-113),** *Journal of Chemical and Engineering Data,* 23(2):113-118, 1978 (6 pages, rdb3918)

1,1,2-trifluoro-1,2,2-trichloroethane, equation of state (EOS), thermodynamic properties

R-114

A. F. Benning and R. C. McHarness, **Thermodynamic Properties of Freon 114 Refrigerant,** technical bulletin T-114D, E. I. duPont de Nemours and Company, Incorporated, Wilmington, DE, 1966 (rdb6810)

R-114, thermophysical data

Y. Higashi, M. Uematsu, and K. Watanabe (Keio University, Japan), **Measurements of the Vapor-Liquid Coexistence Curve and Determination of the Critical Parameters for Refrigerant 114,** *Bulletin of the Japan Society of Mechanical Engineers* (JSME), 28(246):2968-2973, 1985 (6 pages, rdb-7C40)

R-114, thermodynamic properties, thermophysical data

K. R. Hules (Sperry Corporation) and D. P. Wilson (AlliedSignal Incorporated, then Allied Chemical Corporation), **An Interim Engineering Model of the Thermodynamic Properties of 1,2-Dichlorotetrafluoroethane, Refrigerant R-114,** *Proceedings of the Eighth Thermophysical Properties Symposium* (National Bureau of Standards, Gaithersburg, MD, 15-18 June 1981), edited by J. V. Sengers, American Society of Mechanical Engineers (ASME), New York, NY, 11:370-379, 1982 (12 pages with 11 figures and 5 tables, available from JMC as RDB3929)

R-114, modified Martin-Hou (MH) equation of state (EOS), 1,2-dichloro-1,1,2,2-tetrafluoroethane

M. Kriebel, H. J. Löffler, and H. Matthias, **Thermodynamische Eigenschaften binärer Gemische aus Tetrafluordichloräthan (R114) and Kältemaschinenölen**, [Thermodynamic Properties of Binary Mixtures of Dichlorotetrafluoroethane (R-114) and Lubricating Oils] *Kältetechnik-Klimatisierung*, Germany, 18(7):261-267, 1966 (7 pages in German, rdb3B60)

R-114, refrigerant-lubricant (RL) properties, thermophysical data, 1,2-dichloro-1,1,2,2-tetrafluoroethane

J. J. Martin (University of Michigan), **Thermodynamic Properties of Dichlorotetrafluoroethane**, *Journal of Chemical and Engineering Data*, 5(3):-334-336, July 1960 (3 pages, rdb6811)

thermodynamic properties of R-114; thermophysical data

D. P. Wilson (AlliedSignal Incorporated, then Allied Chemical Corporation) and K. R. Hules (Sperry Corporation), **Experimental Study of the Thermodynamic Properties of 1,2-Dichlorotetrafluoroethane**, *Proceedings of the Eighth Thermophysical Properties Symposium* (National Bureau of Standards, Gaithersburg, MD, 15-18 June 1981), edited by J. V. Sengers, American Society of Mechanical Engineers (ASME), New York, NY, II:361-369, 1982 (11 pages with 3 figures and 6 tables, RDB6812)

R-114 [actually R-114/114a (93/7)], measurements of pressure-volume temperature (PVT) properties at 17-234 °C (62-453 °F) and 0.2-10.4 MPa (24-1514 psia) using a high pressure, constant volume and mass apparatus, which is described; 13 isochores were generated in the vapor, supercritical dense gas, and compressed liquid regions; new critical constants were determined; reviews measurements by others, noting that most were on commercial R-114, actually an isomeric blend of R-114/114a (95/5); relations for liquid density, vapor pressure, and ideal gas heat capacity; modified Martin-Hou (MH) equation of state (EOS); vibrational fundamentals for the trans and gauche isomers of R-114

Thermophysical Properties of Refrigerants (R-114, 1,2-dichlorotetrafluoroethane), Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, March 1986 (162 pages with 23 figures and 46 tables, in both Japanese and English, RDB0404)

This comprehensive volume summarizes critical, thermodynamic, transport, physical, chemical, compatibility, and other data available on R-114 (1,2-dichloro-1,1,2,2-tetrafluoroethane). Included are tabular data and/or plots for PVT properties, enthalpy, entropy, isobaric and isochoric specific heat capacity, specific heat ratio, speed of sound, surface tension, viscosity, kinematic viscosity, thermal conductivity, thermal diffusivity, Prandtl number, solubility, refractive index, dielectric constant, volume resistivity, and dielectric strength. An extended Martin Hou equation of state is presented and compared to other equations and data. Relations also are presented for key equilibrium properties. Data are tabulated for the solubility of R-114 in water, moisture contents of saturated R-114 liquid and vapor, and R-114 in both a naphthenic mineral oil and a synthetic polyperfluoroether lubricant. Limited data on hydrolysis rates, stability of R-114 in the presence of metals and oil, and compatibility with other materials are outlined. Published safety data, including toxicity and flammability, are summarized. The volume contains an extensive list of references as well as discussion of the ranges and differences among property sources identified. An introductory section outlines conversions among several metric systems, including SI, and inch-pound units. An appendix summarizes quality requirements for compliance with the Japanese Industrial Standards (JIS) and specifically JIS K1528-1982. R-114 also is regulated as a "liquefied gas" by the Japanese Regulation on High-Pressure Gases.

R-115

J. G. Aston, P. E. Wills, and T. P. Zolki, **The Heat Capacities from 10.9 K, Heats of Transition, Fusion and Vaporization, Vapor Pressures and Entropy of Pentafluorochloroethane, The Barrier Hindering Internal Rotation**, *Journal of the American Chemical Society*, 77:3939-3941, 1955 (3 pages, rdb7C44)

R-115 (chloropentafluoroethane) from -262 °C (-440 °F), thermodynamic properties, thermophysical data

E. Hahne, U. Groß, and Y. W. Song (Universität Stuttgart, Germany), **The Thermal Conductivity of R-115 in the Critical Region,** *International Journal of Thermophysics,* Plenum Publishing Corporation, Brugge, Belgium, 10:687-700, 1989 (14 pages, rdb-5641)

thermodynamic properties of R-115; thermophysical data

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H. J. Löffler and W. Schulz, **Thermodynamische Eigenschaften binärer Gemische aus Pentafluormonochloräthan (R115) and Kältemachinenölen** [Thermodynamic Properties of Binary Mixtures of Chloropentafluoroethane (R-115) and Refrigeration Oils], *Kältetechnik-Klimatisierung*, 18(1):9-15, 1966 (7 pages in German, rdb4932)

thermophysical data, refrigerant-lubricant mixtures

W. H. Mears, E. Rosenthal, and J. V. Sinka (Allied-Signal Incorporated, then Allied Chemical Corporation), **Pressure-Volume-Temperature Behavior of Pentafluoromonochloroethane,** *Journal of Chemical and Engineering Data*, 11(3):338-343, July 1966 (6 pages, rdb4654)

R-115, thermodynamic properties, thermophysical data

R-123

A. R. H. Goodwin, D. R. Defibaugh, G. Morrison, and L. A. Weber (National Institute of Standards and Technology, NIST), **The Vapor Pressure of 1,1-Dichloro-2,2,2-trifluoroethane (R123),** *International Journal of Thermophysics,* 13(6):999-1009, November 1992 (11 pages with 1 figure and 1 table, copies available from JMC as RDB3711)

thermodynamic properties of R-123 (2,2-dichloro-1,1,1-trifluoroethane); measurements by ebulliometric and static techniques for -17 to 181 °C (2-357 °F); correlation for the vapor pressure; thermophysical data

U. Hammerschmidt and W. Hemminger, **Die Wärmeleitfähigkeit von Monochlordifluormethan (R22) und von Dichlortrifluorethan (R123) im Temperaturbereich von 30 bis 190 °C bei Atmosphärendruck** [The Thermal Conductivity of Monochlorodifluoromethane (R-22) and 2,2-Dichloro-1,1,1-trifluoroethane (R-123) in the Temperature Range from 30 to 190 °C (86 to 374 °F) at Atmospheric Pressure], *DKV Jahrestagung* [Proceedings of the DKV Annual Meeting] (Hannover, Germany, 1989), Deutscher Kälte- and Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), 397-410, 1989 (14 pages in German, rdb8461)

thermal conductivity of R-22 and R-123: transport properties, thermophysical data

A. Laesecke, R. A. Perkins, and J. B. Howley (National Institute of Standards and Technology, NIST), **An Improved Correlation for the Thermal Conductivity of HCFC123 (2,2-Dichloro-1,1,1-trifluoroethane),** *International Journal of Refrigeration* (IJR), 19(4):231-238, May 1996 (8 pages with 6 figures and 2 tables, copies available from JMC as RDB7949)

transport properties of R-123; presents a survey of existing data, new measurements, and an improved correlation based on the combined data; correlation covers -93 to 207 °C (-136 to 404 °F) and pressures up to 67 MPa (9700 psia) or densities up to 1900 kg/m^3 (119 lb/ft^3); thermophysical data

S. Nakagawa, H. Sato, and K. Watanabe (Keio University, Japan), **Isobaric Heat Capacity Data for Liquid HCFC-123 ($CHCl_2CF_3$, 2,2-Dichloro-1,1,1-trifluoroethane),** *Journal of Chemical and Engineering Data*, 36(2):156-159, 1991 (4 pages, rdb4B67)

thermodynamic properties of R-123; thermophysical data

S. Nakagawa, H. Sato, and K. Watanabe (Keio University, Japan), **Measurements of Isobaric Specific Heat of HCFC-123 in the Liquid State,** *Thermochimica Acta*, 163:203-210, 1990 (8 pages, rdb5337)

thermodynamic properties of R-123; thermophysical data

K. Oguchi, M. Yamagishi, and A. Murano (Kanagawa Institute of Technology, Japan), **Experimental Study of PVT Properties of HCFC-123 ($CHCl_2CF_3$),** *Preprints of the 11th Symposium on Thermophysical Properties* (Boulder, CO, 23-27 June 1991), American Society of Mechanical Engineers (ASME), New York, NY, 1991; republished in *Fluid Phase Equilibria,* 80(4):131-140, 30 November 1992 (10 pages, rdb7964)

presents pressure-volume-temperature (PVT) properties and vapor pressures of R-123 for -20 to 220 °C (-4 to 428 °F) and pressures up to 17 MPa (2500 psia): measurements were made with a constant volume apparatus with uncertainties of less than ±0.005 °C (0.009 °F) and ±2.2 kPa (0.32 psia); provides a correlation of the new experimental data and other available data to a modified Benedict-Webb-Rubin (MBWR) equation of state (EOS); the fit considered the Gibbs function and latent heat along saturation; also presents a correlation of the vapor pressure for temperatures above -20 °C (-4 °F); the experimental data were converted to the 1990 International Temperature Scale for determination of the correlations; thermodynamic properties of R-123; thermophysical data

K. Oguchi and Y. Takaishi (Kanagawa Institute of Technology, Japan), **Measurement of Saturated Liquid Density of HCFC-123,** *Proceedings of the Tenth Japan Symposium on Thermophysical Prop-*

erties (20-22 September 1989), Shizuoka University, Japan, 55-58, 1989 (4 pages, rdb4313)

thermodynamic properties of R-123; thermophysical data

M. Okada and Y. Higashi (Iwaki Meisel University, Japan), **Surface Tension**, *R123 - Thermodynamic and Physical Properties*, edited by M. O. McLinden (National Institute of Standards and Technology, NIST), International Institute of Refrigeration (IIR), Paris, France, section 3, 1995 (rdb7957)

R-123: surface tension, thermodynamic properties, thermophysical data

T. Okubo and A. Nagashima, **Measurement of the Viscosity of HCFC-123 in the Temperature Range 233-418 K and at Pressure up to 20 MPa,** *International Journal of Thermophysics*, 13(3):401-410, 1992 (10 pages, rdb4881)

R-123 transport properties, thermophysical data

C-C. Piao, H. Sato, and K. Watanabe (Keio University, Japan), **An Equation of State for a New Working Fluid HCFC-123,** *Preprints of the 11th Symposium on Thermophysical Properties* (Boulder, CO, 23-27 June 1991), American Society of Mechanical Engineers (ASME), New York, NY, 1991; republished in *Fluid Phase Equilibria*, 80(4):87-98, 30 November 1992 (12 pages with 13 figures and 5 tables, RDB9135)

presents a 21 coefficient, virial equation of state (EOS) for R-123: EOS is described as effective in the entire fluid phase of pressures up to 15 MPa (2200 psia), temperatures from -3 to 277 °C (26 to 530 °F), and densities from 0 to 1600 kg/m^3 (0 to 100 lb/ft^3); thermodynamic properties; thermophysical data

C-C. Piao, H. Sato, and K. Watanabe (Keio University, Japan), **An Equation for a New Working Fluid HCFC-123**, *Fluid Phase Equilibria*, 80:122-129, 1991 (7 pages, rdb5481)

thermodynamic properties of R-123; thermophysical data

C-C. Piao, H. Sato, and K. Watanabe (Keio University, Japan), **PVT and Vapor Pressure Measurements on 1,1-Dichloro-2,2,2-trifluoroethane** [2,2-dichloro-1,1,1-trifluoroethane] **(HCFC-123)**, *Journal of Chemical and Engineering Data*, 36(4):398-403, 1991 (6 pages with 9 figures and 4 tables, RDB5462)

presents pressure-volume-temperature (PVT) measurements of R-123 by a constant-volume method; provides comparisons to other studies; tabulates a new and published determinations of the critical parameters; thermophysical data

M. Takahashi, C. Yokoyama, and S. Takahashi, **Gas Viscosities of HCFC-123 and HCFC-123a,** *Proceedings of the Eleventh Japan Symposium on Thermophysical Properties*, 115-118, 1990 (4 pages, rdb3923)

R-123, R-123a, viscosity, transport properties, thermophysical data

Y. Tanaka and T. Sotani, **Thermal Conductivity and Viscosity of 2,2-Dichloro-1,1,1-trifluoroethane (HCFC-123),** *International Journal of Thermophysics*, 17:293-328, 1996 (36 pages, rdb8434)

transport properties of R-123: thermal conductivity; viscosity; thermophysical data

Y. Tanaka and T. Sotani, **Transport Properties (Thermal Conductivity and Viscosity)**, *R123 -Thermodynamic and Physical Properties*, edited by M. O. McLinden (National Institute of Standards and Technology, NIST), International Institute of Refrigeration (IIR), Paris, France, 1995 (rdb7958)

R-123: thermal conductivity, viscosity, thermophysical data

S. Tanikawa, Y. Kabata, H. Sato, and K. Watanabe (Keio University, Japan), **Measurements of the Critical Parameters and the Vapor-Liquid Coexistence Curve in the Critical Region of HCFC-123,** *Journal of Chemical and Engineering Data*, 35(4):381-385, 1990 (5 pages, rdb5465)

thermodynamic properties of R-123; thermophysical data

N. E. Ulen, S. G. Penoncello, and R. T. Jacobsen (University of Idaho), **Fundamental Equation of State for 1,1-Dichloro-2,2,2-trifluoroethane (HCFC-123)** [2,2-dichloro-1,1,1-trifluoroethane], paper 93-WA/HT-27 (Winter Annual Meeting, New Orleans, LA, 28 November - 3 December 1993), American Society of Mechanical Engineers (ASME), New York, NY, 1993 (6 pages, rdb8932)

presents a fundamental equation (FEQ) for R-123: this equation of state (EOS) is valid from -107 to 252 °C (-161 to 485 °F) at pressures to 40 MPa (5800 psia) with temperatures in the International Temperature Scale of 1990 (ITS-90); also presents ancillary functions for the vapor pressure, saturated liquid density, and saturated vapor density; the equation are based on a stepwise, linear, least squares regression algorithm used in a multi-property fit to vapor pressure, density, temperature, heat capacity, and speed of sound data; compares the FEQ to the experimental data to verify the accuracy

J. E. S. Venart, **Transient Hot-Wire Measurements of the Thermal Conductivity of R123**, University of New Brunswick, Fredericton, Canada, 1993 (rdb-8454)

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transport properties of R-123; thermophysical data

L. A. Weber and J. M. H. Levelt Sengers (National Institute of Standards and Technology, NIST), **Critical Parameters and Saturation Densities of 1,1-dichloro-2,2,2-trifluoroethane** [2,2-dichloro-1,1,1-trifluoroethane], *Fluid Phase Equilibria,* 55:241-249, 1990 (9 pages with 2 figures and 1 table, RDB0915)

This paper describes measurements to determine the critical parameters (temperature and density) as well as densities along the liquid-vapor phase boundary of R-123. It describes and schematically shows the optical cell employed. It also outlines the experimental procedures used for the measurements. The measured data are tabulated and an empirical correlation and uncertainty analysis are presented. The critical temperature and density were found to be 183.72 °C (362.70 °F) and 550 kg/m^3 (34.3 lb/cf), respectively. The critical pressure was calculated from vapor pressure data to be 3674 kPa (532.9 psia), which yields a value of 0.269 for the critical compressibility factor, Z_c. Measurement temperatures varied from 25 °C (77 °F) to the critical point for the saturated liquid and from 160 °C (320 °F) to the critical point for saturated vapor.

L. A. Weber (National Institute of Standards and Technology, NIST), **Vapor Pressures and Gas Phase PVT Data for 1,1-Dichloro-2,2,2-trifluoroethane** [2,2-dichloro-1,1,1-trifluoroethane], *Journal of Chemical and Engineering Data*, 35(3):237-240, July 1990 (4 pages with 2 figures and 4 tables, available from JMC as RDB0910)

New data are presented for the vapor pressure and gas-phase PVT surface of R-123 in the temperature range 338-453 K (149-356 °F) at densities up to 0.67 mol/L. The data have been represented analytically to demonstrate the precision and to facilitate calculation of thermodynamic properties.

B. A. Younglove and M. O. McLinden (National Institute of Standards and Technology, NIST), **An International Standard Equation-of-State Formulation of the Thermodynamic Properties of Refrigerant 123 (2,2-Dichloro-1,1,1-trifluoroethane)**, *Journal of Physical and Chemical Reference Data*, 23(5):731-779, 1994 (49 pages with 16 figures and 7 tables, RDB7607)

modified Benedict-Webb-Rubin (MBWR) equation of state (EOS) for R-123 based on measured properties and data available from the literature: provides coefficients for the 32 coefficient EOS and for ancillary equations representing the vapor pressure, saturated liquid and saturated vapor densities, and ideal gas heat capacity; while the measurements cover differing ranges of temperature and pressure, the MBWR formulation is applicable along the saturation line and in the liquid, vapor, and supercritical regions at temperatures from -107 to 223 °C (-161 to 440 °F) with pressures to 40 MPa (5800 psia) and densities to 11.6 mol/L (0.4 mol/ft^3) or 1774 kg/m^3 (111 lb/ft^3); this EOS was selected as an international standard by a group working under the auspices of the International Energy Agency (IEA)

Forane(R) 123, technical digest, Elf Atochem North America, Incorporated, Philadelphia, PA, undated circa 1994 (4 pages with 4 tables, available from JMC as RDB4767)

This bulletin supplies information on R-123 for use in low-pressure chillers, both in new equipment and retrofit of R-11 equipment. It compares the physical and environmental properties of R-11 and R-123, and provides a tabular data summary for them in inch-pound (IP) units. The table lists the chemical formula, molecular weight, normal boiling and freezing points, heat of vaporization, vapor and liquid density at the boiling point and 27 °C (80 °F), critical parameters (temperature, pressure, and density), specific heat of the liquid at the same temperature and of the vapor at atmospheric pressure, ozone depletion potential (ODP), and halocarbon global warming potential (HGWP). The table also shows both fluids to be non flammable. A second table gives the saturated vapor pressures of R-11 and R-123 for -40 to 93 °C (-40 to 200 °F). A third presents the saturated vapor pressure and liquid and vapor densities and enthalpies for the same temperature range. The document briefly reviews operating and retrofit considerations with attention to performance, lubrication, and material compatibility. It also comments on personal exposure and safe handling. The digest concludes with container identification for R-123 and other alternative refrigerants. Elf Atochem's product name for R-123 is Forane® 123.

Genetron(R) 123, technical bulletin B-525-646, AlliedSignal Incorporated, Morristown, NJ, February 1993, May 1993, September 1993, November 1993, and February 1994 (4 pages with 3 tables, RDB-3452)

This bulletin supplies information on R-123, described as a replacement for R-11 in centrifugal chillers. It provides physical property data, in inch-pound (IP) units, including the chemical formula, molecular weight, atmospheric boiling point, corresponding heat of vaporization, critical parameters (temperature, pressure, and density), flammability, and ozone depletion potential. It also indicates the liquid density and specific heats of the liquid and vapor at 30 °C (86 °F). It then presents a tabular comparison of performance for R-11 and R-123. The report provides tabular thermodynamic properties (pressure, density, vapor volume, liquid and vapor enthalpy and entropy, and latent heat of vaporization) for -18 to 71 °C (0 to 160 °F). Formulae are provided to calculate thermodynamic properties including vapor pressure, ideal gas heat capacity, and liquid density correlations. Estimated coefficients are presented for a Martin-Hou equation of state. AlliedSignal's product name for R-123 is Genetron® 123.

Thermodynamic Properties of HCFC-123 (2,2-Dichloro-1,1,1-trifluoroethane), technical information report T-123-ENG (H-47753), DuPont Chemicals, Wilmington, DE, January 1993 (40 pages with 1 figure and 2 tables, available from JMC as RDB-3422)

This report provides thermodynamic property data for R-123 in inch-pound (IP) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a modified Benedict-Webb-Rubin (MBWR) equation of state and an ideal gas heat capacity equation at constant pressure. It also gives a Martin-Hou equation of state (EOS), fit from MBWR data, and a corresponding ideal gas heat capacity equation at constant vapor. It supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (pressure and liquid and vapor volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -101 to 183 °C (-150 to 362 °F). A set of tables presents volume, enthalpy, entropy, heat capacity at constant pressure, heat capacity ratio (dimensionless Cp/Cv), and velocity of sound data for superheated vapor at constant pressure for 7-3450 kPa (1-500 psia). The new tables are based on experimental data from the National Institute of Standards and Technology (NIST). The report concludes with a pressure-enthalpy diagram. DuPont's product names for R-123 are Suva® 123 Refrigerant and Suva® Centri-LP Refrigerant.

Thermodynamic Properties of HCFC-123 (2,2-Dichloro-1,1,1-trifluoroethane), technical information report T-123-SI (H-47754), DuPont Chemicals, Wilmington, DE, January 1993 (32 pages with 1 figure and 2 tables, available from JMC as RDB3423)

This report provides thermodynamic property data for R-123 in metric (SI) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature pressure, density, and specific volume). It then presents a modified Benedict--Webb-Rubin (MBWR) equation of state and an ideal gas heat capacity equation at constant pressure. It also gives a Martin-Hou equation of state (EOS), fit from MBWR data, and a corresponding ideal gas heat capacity equation at constant vapor. It supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (pressure and liquid and vapor volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -100 to 183 °C (-148 to 362 °F). A set of tables presents volume, enthalpy, entropy, heat capacity at constant pressure, heat capacity ratio (dimensionless Cp/Cv), and velocity of sound data for superheated vapor at constant pressure for 10-3600 kPa (1-520 psia). The new tables are based on experimental data from the National Institute of Standards and Technology, NIST). The report concludes with a pressure-enthalpy diagram. DuPont's product names for R-123 are Suva(R) 123 Refrigerant and Suva(R) Centri-LP Refrigerant.

R-124

R. Bender, K. Bier, and G. Maurer, **Heat Capacity at Constant Pressure and Joule-Thomson Coefficient of Monochloro-1,2,2,2-tetrafluoroethane** [2-chloro-1,1,1,2-tetrafluoroethane], *Journal of Chemical Thermodynamics*, 12:335-341, 1980 (8 pages, rdb4222)

R-124, thermodynamic properties, thermophysical data

S. J. Boyes and L. A. Weber (National Institute of Standards and Technology, NIST), **Vapor Pressures and Gas-Phase PVT Data for 1-Chloro-1,2,2,2-tetrafluoroethane** [2-chloro-1,1,1,2-tetrafluoroethane], *International Journal of Thermophysics*, 15(3):443-460, May 1994 (18 pages with 4 figures and 6 tables, limited copies available from JMC as RDB4893)

This paper presents new, very precise, thermodynamic data on R-124 in the temperature range of 5-150 °C (41-302 °F). The measured data include vapor pressures and the gas-phase pressure-volume-temperature (PVT) surface. The paper explains the apparatus and measurement techniques. It describes and graphically shows the influence of a volatile impurity, determined to be R-32. Compensating corrections to the data are outlined. The paper tabulates the measured data, and provides a fit to a

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Wagner equation for vapor pressures and to a virial PVT surface equation. It compares the findings to existing data in the literature, and also presents calculated values of saturated vapor density.

B. de Vries, R. Tillner-Roth, and H. D. Baehr (Universität Hannover, Germany), **Thermodynamic Properties of HCFC-124**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:582-589, 1995 (8 pages with 7 figures and 2 tables, rdb7905)

R-124, thermodynamic properties, thermophysical data: overview of available experimental data and comparisons between sources; Helmholtz free energy equation of state (EOS)

M. Fukushima and K. Watanabe (Keio University, Japan), **Thermodynamic Properties of HCFC-124**, *Nippon Reito Kyokai Ronbunshu* [Transactions of the JAR], Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 10:75-86, 1993 (10 pages in Japanese, rdb9124)

thermodynamic properties of R-124, thermophysical data

H. Kubota, Y. Tanaka, T. Makita, H. Kashiwagi, and M. Noguchi, **Thermodynamic Properties of 1-Chloro-1,2,2,2-tetrafluoroethane (R-124)** [2-chloro-1,1,1,2-tetrafluoroethane], *International Journal of Thermophysics,* 9(1):85-101, 1988 (17 pages, rdb2332)

thermophysical data

I. R. Shankland, R. S. Basu, and D. P. Wilson (AlliedSignal Incorporated), **Thermophysical Properties of HCFC-124: An Environmentally Acceptable Refrigerant**, paper 3418, *Transactions* (Annual Meeting, St. Louis, MO, 9-13 June 1990), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 96(2):317-322, 1990; republished in *CFC Alternatives*, technical data bulletin 6(1), ASHRAE, 19-24, June 1990 (6 pages with 3 figures and 11 tables, RDB4123)

R-124, thermophysical data

M. Takahashi, C. Yokoyama, and S. Takahashi, **Gas Viscosity of HFC-124** [sic, HCFC-124] **at High Pressures**, *Proceedings of the 13th Japan Symposium on Thermophysical Properties*, Akita, Japan, 347-350, 1992 (4 pages, rdb3925)

R-124, HCFC-124, transport data

Thermodynamic Properties of HCFC-124 (2-Chioro-1,1,1,2-tetrafluoroethane), technical Information report T-124-ENG (H-47755),DuPont Chemicals, Wilmington, DE, January 1993 (36 pages with 1 figure and 2 tables, available from JMC as RDB3424)

This report provides thermodynamic property data for R-124 in inch-pound (IP) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a modified Benedict-Webb-Rubin (MBWR) equation of state and an ideal gas heat capacity equation at constant pressure. It also gives a Martin-Hou equation of state (EOS), fit from MBWR data, and a corresponding ideal gas heat capacity equation at constant vapor. It supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (pressure and liquid and vapor volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -101 to 122 °C (-150 to 252 °F). A set of tables presents volume, enthalpy, entropy, heat capacity at constant pressure, heat capacity ratio (dimensionless Cp/Cv), and velocity of sound data for superheated vapor at constant pressure for 7-3450 kPa (1-500 psia). The new tables are based on experimental data from the National Institute of Standards and Technology (NIST). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-124 is Suva® 124 Refrigerant.

Thermodynamic Properties of HCFC-124 (2-Chloro-1,1,1,2-tetrafluoroethane), technical information report T-124-SI (H-47756), DuPont Chemicals, Wilmington, DE, January 1993 (32 pages with 1 figure and 2 tables, available from JMC as RDB3425)

This report provides thermodynamic property data for R-124 in metric (SI) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a modified Benedict-Webb-Rubin (MBWR) equation of state and an ideal gas heat capacity equation at constant pressure. It also gives a Martin-Hou equation of state (EOS), fit from MBWR data, and a corresponding ideal gas heat capacity equation at constant vapor. It supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (pressure and liquid and vapor volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -100 to 122 °C (-148 to 252 °F). A set of tables presents volume, enthalpy, entropy, heat capacity at constant pressure, heat capacity ratio (dimensionless Cp/Cv), and velocity of sound data for superheated vapor at constant pressure for 10-3600 kPa (1-520 psia). The new tables are based on experimental data from the National Institute of Standards and Technology (NIST). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-124 is Suva(R) 124 Refrigerant.

R-125

C. Baroncini, G. Giuliani, G. Latini, F. Polonara (Università degli Studi di Ancona, Italy), and R. Camporese (Consiglio Nazionale della Ricerche, CNR, Italy), **Experimental Evaluation of Thermodynamic Properties of Refrigerants R125 (CHF_2CF_3)**, *Energy Efficiency and Global Warming Impact* (proceedings of the meetings of Commissions B1 and B2, Ghent, Belgium 12-14 May 1993), International Institute of Refrigeration (IIR), Paris, France, 207-213, 1993 (7 pages with 3 figures and 2 tables, rdb5318)

R-125, thermophysical data, measurement, vapor pressure, PVT properties, Redlich-Kwong-Soave (RKS) equation of state (EOS)

G. Bigolaro, R. Camporese (Consiglio Nazionale delle Ricerche, CNR, Italy), G. Cortella, P. Romagnoni (Università di Udine, Italy), and M. Scattolini (CNR), **Propriétés Thermodynamiques du Réfrigérant Pentafluoroethane (R125)** [Thermodynamic Properties of Refrigerant Pentafluoroethane (R-125)], *International Journal of Refrigeration* (IJR), 13(8):44-49, November 1990 (6 pages, rdb5457)

thermophysical data

S. J. Boyes and L. A. Weber (National Institute of Standards and Technology, NIST), **Vapour Pressures and Gas-Phase (p, ro(n), T) Values for CF_3CHF_2 (R125),** *Journal of Chemical Thermodynamics*, 27:163-174, 1995 (12 pages with 5 figures and 7 tables, RDB8C37)

thermodynamic properties of R-125: reports measurements of the vapor pressures and the pressure-density-temperature surface for 0-90 °C (32-194 °F); presents correlations of the vapor pressure from -53 °C (-64 °F) to the critical point temperature of 66.15 °C (151.07 °F); also presents a virial equation for the pressure-density-temperature surface and derived second and third virial coefficients; thermophysical data

N. Cohen and S. W. Benson, *Journal of Physical and Chemical Reference Data*, 91:162-175, 1987 (14 pages, rdb5941)

R-125

D. R. Defibaugh and G. Morrison (National Institute of Standards and Technology, NIST), **Compressed Liquid Densities and Saturation Densities of Pentafluoroethane (R125)**, *Fluid Phase Equilibria*, 80:157-166, 1992 (10 pages with 4 figures and 4 tables, RDB4B26)

thermodynamic properties of R-125: density measurements with a vibrating tube densimeter for 2-96 °C (35-205 °F) and 1600-6300 kPa (232-914 psia); 32 parameter modified Benedict-Webb-Rubin (MBWR) equation of state (EOS); thermophysical data

M. Fukushima and S. Ohotoshi (Asahi Glass Company, Limited, Japan), **Thermodynamic Properties of HFC-125**, *Proceedings of the 13th Japan Symposium on Thermophysical Properties*, Akita, Japan, 49-52, 1992 (4 pages, rdb4B25)

thermodynamic properties of R-125; thermophysical data

N. J. Hewitt, J. T. McMullan, R. H. Evans, and B. Mongey (University of Ulster, UK), **Martin-Hou, Peng-Robinson and Redlich-Kwong-Soave Equations of State for HFC-125**, *International Journal of Energy Research* (IJER), 20(1):33-39, January 1996 (7 pages with 1 figure and 7 tables, RDB7C03)

presents coefficients for the Martin-Hou (MH), Peng-Robinson (PR), and Redlich-Kwong-Soave (RKS) equations of state (EOSs) for R-125: notes that the three EOSs produce reasonable agreement for property determination, but that the results from them should be used only as an estimate in performance calculations; the accuracy of the PR EOS decreases as the saturated temperature approaches the critical temperature, but it is described as very useful when measured property are limited and some are of doubtful accuracy; the more complex MH and RKS EOSs are preferred for a full set of measured refrigerant data

M-F. Liu and L-Z. Han (Tsinghua University, China), **Experimental Research on Surface Tension of HFC-125**, *Qinghua Daxue Xuebao* [Journal of Tsinghua University], Beijing, China 35(2):17-21, April 1995 (5 pages, rdb7A37)

presents surface tension data for R-125 measured using both an absolute capillary rise technique and a differential capillary rise technique at -40 °C (-40 °F): the separate experimental results of the two methods were found to be consistent; deviations between the two methods are ≤0.2%; authors propose a Van der Waals surface tension correlation using the new data

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M-F. Liu, L-Z. Han, and M-S. Zhu (Tsinghua University, China), **Surface Tension of Pentafluoroethane (HFC-125)**, *International Journal of Thermophysics*, 15(5):941-948, 1994 (8 pages with 5 figures and 2 tables, RDB8C23)

measurements of the surface tension of R-125 with both an absolute capillary rise technique and a differential capillary rise method for -40 to 61.1 °C (-40 to 140 °F); correlation with a van der Waals equation; tabulates the measured and predicted data; concludes that the measured data fit the correlation with deviations of less than 0.8%

Y. Monluc, T. Sagawa, H. Sato, and K. Watanabe (Keio University, Japan), **Thermodynamic Properties of HFC-125**, paper B101, *Proceedings of the Twelfth Japan Symposium on Thermophysical Properties*, 65-68, 1991 (4 pages with 5 figures and 1 table, RDB2427)

This paper reports experimental data for R-125, including vapor pressure and PVT properties in the vapor phase. Vapor pressures were measured for 303-339 K (86-151 °F) and correlated; the critical pressure (3.633 MPa, 527.3 psia) also was determined based on a critical temperature previously determined by M. O. McLinden of 339.4 K (151.3 °F). PVT properties were measured along five isochores for temperatures of 240-423 K (-27 to 302 °F), pressures of 1.5-8.6 MPa (220-1250 psia), and densities of 97-446 kg/m^3 (6-28 lb/cf). The experimental approach and regression equation are presented and vapor pressure measurements are tabulated and plotted. The PVT properties for the vapor phase also are plotted and compared to other published data.

I. I. Orekhov, A. V. Kletskii, Y. A. Laptev, and O. B. Tsvetkov (Saint Petersburg State Academy of Refrigeration and Food Technologies, Russia), **Pentafluoroethane (HFC-125). Equation of State and Transport Properties**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:457-464, 1995 (8 pages with 1 figure and 2 tables, rdb7847)

R-125, measurements of thermodynamic properties, equation of state (EOS), thermal conductivity, thermophysical properties

C-C. Piao and M. Noguchi (Daikin Industries, Limited, Japan), **Thermodynamic Properties HFC-125**, *Proceedings of the 15th Japan Symposium on Thermophysical Properties,* Japan, 9-12, 1994 (4 pages with 7 figures, in Japanese with English abstract and figures, RDB7851)

presents an 18-coefficient, modified Benedict-Webb-Rubin (BWR) equation of state (EOS) for R-125; EOS was determined from published data by a least-squares method; thermophysical data

O. B. Tsvetkov, A. V. Kletskii, Y. A. Laptev, A. J. Asambaev, and I. A. Zausaev (Saint Petersburg, Technological Institute of Refrigeration, Russia), **Thermal Conductivity and PVT Measurements of Pentafluoroethane (Refrigerant HFC-125)**, *International Journal of Thermophysics,* 16(5):1185-1192, September 1995 (8 pages, rdb7C61)

measurements of the thermal conductivity of R-125 by transient and steady-state coaxial cylinder methods at temperatures from -86 to 146 °C (-123 to 295 °F) and pressures from atmospheric to 6 MPa (870 psia): the experimental approach was validated by measuring the thermal conductivity of R-12 and R-22 and the estimated uncertainty of the results is ±2-3%; vapor pressure and PVT measurements were made using a constant-volume apparatus for the temperature range -10 to 170 °C (14-338 °F), pressures up to 6 MPa (870 psia), and densities of 36-516 kg/m^3 (2-32 lb/ft^3)

L. C. Wilson, W. V. Wilding, G. M. Wilson, R. L. Rowley, V. M. Felix, and T. Chisholm-Carter (Wiltec Research Company), **Thermophysical Properties of HFC-125**, *Preprints of the 11th Symposium on Thermophysical Properties* (Boulder, CO, 23-27 June 1991), American Society of Mechanical Engineers (ASME), New York, NY, 1991; republished in *Fluid Phase Equilibria,* 80(4):167-177, 30 November 1992 (11 pages, rdb3927)

presents measurements of thermophysical properties of R-125; they include vapor pressures, critical temperature, critical pressure, critical density, pressure-volume-temperature (PVT) data, liquid and vapor heat capacities, isobaric enthalpy differences, liquid and vapor viscosities, and liquid and vapor thermal conductivities; provides a BWRS equation of state (EOS) to correlate the PVT and vapor pressure data and to predict enthalpy departures; compares the experimental data to published findings from other studies

R-134

T. Tamatsu, H. Sato, and K. Watanabe (Keio University, Japan), **Measurements of the Pressure-Volume-Temperature Properties of 1,1,2,2-Tetrafluoroethane (HFC-134)**, *Journal of Chemical and Engineering Data*, 37:216-219, 1992 (4 pages, rdb-5478)

R-134, thermodynamic properties, thermophysical data

T. Tatoh, S. Kuwabara, H. Sato, and K. Watanabe (Keio University, Japan), **Measurements of the Vapor-Liquid Coexistence Curve in the Critical Region and Critical Parameters of 1,1,2,2-Tetrafluoroethane (HFC-134)**, *Journal of Chemical and Engineering Data*, 38:116-118, 1993 (3 pages, rdb5467)

R-134, thermodynamic properties, thermophysical data

R-134a

M. J. Assael (Aristotle University, Greece), Y. Nagasaka (Keio University, Japan), C. A. Nieto de Castro (Universidade de Lisboa, Portugal), R. A. Perkins (National Institute of Standards and Technology, NIST, USA), K. Ström (Chalmers University of Technology, Sweden), E. Vogel (Universität Rostock, Germany), and W. A. Wakeham (Imperial College, UK**), Status of the Round Robin on the Transport Properties of R-134a**, *International Journal of Thermophysics,* 16:63-78, 1996 (16 pages, rdb8949)

interim results of an international project to investigate discrepancies in findings of different researchers for the viscosity and thermal conductivity of refrigerant R-134a; investigation involves new measurements with a single sample to test whether the reported differences stem from sample purity; project is coordinated by the Subcommittee on Transport Properties of Commission 1.2 of the International Union of Pure and Applied Chemistry (IUPAC)

C. Baroncini, G. Giuliani, M. Pacetti, and F. Polonara (Università degli Studi di Ancona, Italy), **Experimental Study of Thermodynamic Properties of 1,1,1,2-Tetrafluoroethane (R134a)**, *Thermophysical Properties of Pure Substances and Mixtures for Refrigeration* (proceedings of the meeting of IIR Commission B1, Herzlia, Israel, March 1990), International Institute of Refrigeration (IIR), Paris, France, 83-88, 1990 (6 pages with 4 figures and 3 tables, RDB4B45)

R-134a, thermodynamic properties, thermophysical data

R. S. Basu and D. P. Wilson (AIlied-Signal Incorporated), **Thermophysical Properties of 1,1,1,2-Tetrafluoroethane (R-134a)**, *Proceedings of the Tenth Thermophysical Properties Symposium* (Gaithersburg, MD, 20-23 June 1988); republished in the *International Journal of Thermophysics,* 10(3):591-603, May 1989 (13 pages with 3 figures and 9 tables, RDB0514)

R-134a, thermodynamic properties, thermophysical data: critical parameters (temperature, pressure, and density); measured vapor pressure, liquid density, pressure-volume-temperature (PVT), and ideal-gas heat capacity data and correlations; Martin-Hou (MH) equation of state (EOS)

A. C. Cleland, **Polynomial Curve-Fits for Refrigerant Thermodynamic Properties: Extension to Include R134a**, *International Journal of Refrigeration* (IJR), 17(4):245-249, 1994 (5 pages, rdb9929)

R-134a, simulation, thermodynamic properties, thermophysical data

A. V. Dobrokhotov, A. G. Grebenkov, E. E. Ustjushanin, V. V. Altunin, V. P. Dzelezny, A. V. Maslennikov, and O. B. Tsvetkov (Moscow Power Engineering Institute, Russia), **Equation of State and Thermophysic**[al] **Properties for HFC-134a at the Single-Phase Region**, *Energy Efficiency and Global Warming Impact* (proceedings of the meetings of Commissions B1 and B2, Ghent, Belgium 12-14 May 1993), International Institute of Refrigeration (IIR), Paris, France, 175-182, 1993 (8 pages with 1 table, rdb5314)

thermodynamic and transport properties of R-134a: density, isobaric heat capacity, sound velocity, viscosity, and thermal conductivity; thermophysical data

A. V. Dobrokhotov, A. V. Maslennikov, J. V. Semenuk, and E. E. Ustjushanin (Moscow Power Engineering Institute, Russia), **The Density of Refrigerant 134a - Experiment and Generalization**, *Kolloidnyi Tekhnika* [Refrigeration Technology], 7:16-20, 1991 (5 pages, in Russian, rdb5441)

R-134a, thermodynamic properties, thermophysical data

A. R. H. Goodwin and M. R. Moldover (National Institute of Standards and Technology, NIST), **Thermophysical Properties of Gaseous Refrigerants from Speed of Sound Measurements (Apparatus, Model, and Results for 1,1,1,2-Tetrafluoroethane, R-134a)**, *Journal of Chemical Physics*, 93(4):2741-2753, 15 August 1990 (13 pages with 10 figures and 4 tables, available from JMC as RDB-0919)

The speed of sound in gaseous R-134a has been obtained between 233.16 and 340 K from measurements of the frequency of the radial acoustic resonances of a gas-filled spherical cavity. Perfect gas heat capacities and second and third acoustic virial coefficients are used to estimate the density virial coefficients B(T) and C(T) and an effective square-well potential. The estimates of B(T) are consistent with B(T) deduced from high-quality equation-of-state measurements; those for C(T) are slightly inconsis-

please see page 6 for ordering information

tent. The apparatus and its calibration with argon are described.

H. J. R. Guedes and J. A. Zollweg, **Speed of Sound in Liquid R134a***, International Journal of Refrigeration* (IJR), 15(6):381-385, July 1992 (5 pages, rdb4B52)

R-134a, transport properties, thermophysical data

H. Hou, J. C. Holste, B. E. Gammon, and K. N. Marsh (Texas A&M University), **Experimental Densities for Compressed R-134a**, *International Journal of Refrigeration* (IJR), 15(6):365-371, 1992 (17 pages, rdb4A55)

thermodynamic properties of R-134a, thermophysical data

D. G. Friend and M. L. Huber (National Institute of Standards and Technology, NIST), **Thermophysical Property Standard Reference Data from NIST**, *International Journal of Thermophysics*, 15(6):1279-1288, November 1994 (10 pages, rdb-8924)

This paper discusses five computerized databases distributed by the NIST Standard Reference Data (SRD) Program. The databases provide national standards for the properties of pure fluids, an accurate evaluated mixture program focusing on the properties of natural gas mixtures, a predictive package emphasizing hydrocarbon systems up to those with 20 carbon atoms, a database for refrigerant and prospective alternative refrigerant fluids (REFPROP), and the current scientific thermophysical property surfaces for pure water and steam. The databases include both thermodynamic surfaces and representations for transport properties over broad ranges of temperature, pressure, and composition. The paper also discusses research to improve the standards for air and for aqueous systems, including R-717/718 (the binary mixture of ammonia and water) widely used in absorption cycle refrigeration.

M. L. Huber (National Institute of Standards and Technology, NIST), **Structural Optimization of Vapor Pressure Correlations Using Simulated Annealing and Threshold Accepting: Application to R134a**, *Computers and Chemical Engineering*, 18(10):929-932, 1994 (4 pages with 3 tables, RDB7961)

This paper reports the use of two methods, namely simulated annealing (SA) and threshold accepting (TA), to determine a set of optimal terms (the structure) of the vapor pressure correlation for R-134a. The SA algorithm with the Lundy and Mees annealing schedule, and the TA algorithm with the Aarts and Van Laarhoven schedule gave the best performance, based on minimal computational time for a given performance. The authors conclude that SA and TA appear to be versatile, powerful, and computationally simple methods for determining the structure of empirical correlations for thermophysical property data.

M. L. Huber (National Institute of Standards and Technology, NIST) and J. F. Ely (Colorado School of Mines), **A Predictive Extended Corresponding States Model for Pure and Mixed Refrigerants Including an Equation of State for R134a**, *International Journal of Refrigeration* (IJR), 17(1):18-31, January 1994 (14 pages with 14 figures and 9 tables, RDB7945)

R-134a, ECS equation of state (EOS), thermodynamic properties, thermophysical data; extensive reference list for thermodynamic data on R-11, R-12, R-13, R-13B1, R-14, R-22, R-23, R-32, R-114, R-115, R-123, R-124, R-125, R-134, R-141b, R-142b, R-143a, R-152a, and R-C270

M. L. Huber and J. F. Ely (National Institute of Standards and Technology, NIST), **An Equation of State Formulation of the Thermodynamic Properties of R-134a (1,1,1,2-Tetrafluoroethane)**, *International Journal of Refrigeration* (IJR), 15(6):393-400, July 1992 (8 pages with 10 figures and 10 tables, available from JMC as RDB3702)

thermophysical data

M. L. Huber and M. O. McLinden (National Institute of Standards and Technology, NIST), **Thermodynamic Properties of R-134a (1,1,1,2-Tetrafluoroethane)**, *Proceedings of the 1992 International Refrigeration Conference - Energy Efficiency and New Refrigerants*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 11:453-462, July 1992 (10 pages with 4 figures and 9 tables, RDB2828)

R-134a, equation of state (EOS), thermophysical data

Y. Kabata, S. Tanikawa, M. Uematsu, and K. Watanabe (Keio University, Japan), **Measurements of the Vapor-Liquid Coexistence Curve and the Critical Parameters for 1,1,1,2-Tetrafluoroethane**, *International Journal of Thermophysics*, 10(3):605-616, 1989 (12 pages, rdb4119)

thermodynamic properties of R-134a: vapor-liquid equilibria (VLE), thermophysical data

T. Kamimura, N. Watanabe, and M. Fukushima, **An Evaluation as for Thermophysical Properties of R134a, Part 2**, *Proceedings of the 29th High Pressure Conference* (Fujisawa, Japan, 16-18 November 1988), 112-113, 1988 (2 pages, rdb9139) thermodynamic properties of R-134a; thermophysical data

P. M. Kesselman, V. P. Dzelezny, and Y. V. Semenuk (Moscow Power Engineering Institute, Russia), **Thermal Properties of Refrigerant 134a in the Liquid Phase**, *Kolloidnyi Tekhnika* [Refrigeration Technology], 7:9-11, 1991 (3 pages, In Russian, rdb5445)

R-134a, thermodynamic properties, thermophysical data

J. Klomfar, J. Hruby, and O. Sifner, **Measurements of the p-v-T Behavior of Refrigerant R134a in the Liquid Phase**, *International Journal of Thermophysics*, 14(4):, July 1993, with erratum in 16(4):-1031, July 1995 (rdb7A54)

R-134a, thermodynamic properties, thermophysical data

R. Krauss (Universität Stuttgart, Germany), J. Luettmer-Strathmann (University of Maryland, USA), J. V. Sengers (University of Maryland, USA, and National Institute of Standards and Technology, NIST, USA), and K. Stephan (Universität Stuttgart, Germany), **Transport Properties of 1,1,1,2-Tetrafluoroethane (R134a)**, *International Journal of Thermophysics*, 14(4):951-988, July 1993 (38 pages with 23 figures and 6 tables, RDB6401)

This paper presents new equations for the thermal conductivity and viscosity of R-134a. The paper summarizes a critical evaluation of available experimental data, with emphasis on the vapor phase. It outlines the methodology used to correlate the data, which was based on a temperature-dependent dilute gas term, an excess or residual term that accounts for density dependence, and the critical enhancement around the vapor-liquid critical point. A crossover model is presented for the latter along with a new fundamental equation (FEQ) of state (EOS) for the critical region. Tables summarize the saturation properties as a function of temperature for -33 to 101 °C (-27 to 214 °F) and the viscosity and thermal conductivity as a function of pressure and temperature, for 0.1-30.0 MPa (1.5-44 psia) and 17-157 °C (62-314 °F) respectively.

H. Kubota and T. Matsumoto (Kobe University, Japan), **High-Pressure Vapor-Liquid Equilibrium for the System HFC-134a**, *Journal of Chemical Engineering*, Japan, 26:320 ff, 1993 (rdb7639)

thermodynamic properties of R-134a; thermophysical data, VLE

A. Kumagai, H. Mochida, and S. Takahashi, **Revised Viscosities for HFC-134a + Glycol Mixtures from 273 to 353 K**, *International Journal of Thermophysics,* 15:109 ff, 1993 (rdb7640)

R-134a, viscosity for 0-80 °C (32-176 °F), transport properties, thermophysical data

A. Laesecke (National Institute of Standards and Technology, NIST), **Data Reassessment and Full-Surface Correlation of the Viscosity of 1,1,1,2-Tetrafluoroethane (HFC-134a)**, *Journal of Physical and Chemical Reference Data*, 1999 (rdb8222)

transport properties of R-134a; thermophysical data [a private communication from the author indicates that this paper is being revised with publication anticipated in 1999]

A. Laesecke, R. A. Perkins (National Institute of Standards and Technology, NIST, USA), and C. A. Nieto de Castro (Universidade de Lisboa, Portugal), **Thermal Conductivity of R134a**, *Fluid Phase Equilibria*, 80(11):263-274, 1992 (12 pages with 5 figures and 1 table, available from JMC as RDB3708)

transport properties of R-134a; thermophysical data

Y. A. Laptev, O. B. Tsvetkov, A. G. Asambaev (Saint Petersburg State Academy of Refrigeration and Food Technologies, Russia), **Thermal Conductivity of R134a**, *Vestn. Mezhduna. Akad. Holoda,* Russia, 1998(1):21-23, 1998 (3 pages with 3 tables, in Russian, rdb9310)

thermal conductivity of R-134a, transport properties, thermophysical data

G. K. Lavrenchenko, G. Ya. Ruvinskij, S. V. Iljushenko, and V. V. Kanaev (Institute of Energy Conversion Systems, Ukraine), **Thermophysical Properties of Refrigerant R134a**, *International Journal of Refrigeration* (IJR), 15(6):386-392, July 1992 (7 pages, RDB8261)

thermodynamic properties of R-134a; thermophysical data

J. W. Magee and J. B. Howley (National Institute of Standards and Technology, NIST), **Vapour Pressure Measurements on 1,1,1,2-Tetrafluoroethane (R134a) from 180 to 350 K**, *International Journal of Refrigeration* (IJR), 15(6):362-364, July 1992 (3 pages with 2 figures and 2 tables, available from JMC as RDB3704)

This paper summarizes measurements of vapor pressure for R-134a for -93 to 177 °C (-136 to 350 °F) by using an automated static cell. Temperatures and pressures were measured with a platinum resistance thermometer and with calibrated, oscillating quartz-crystal pressure transducers, respectively. The paper reviews the experimental approach, presents the measured data, plots the pressure-temperature relation-

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ship, provides a regression equation, and examines the deviations to it. The results provide highly accurate measurements of vapor pressure for purified R-134a. This work extends the range of available data for R-134a to lower temperatures, more than 60 °C (108 °F) below is normal boiling point.

J. W. Magee (National Institute of Standards and Technology, NIST), **Measurements of Molar Heat Capacity at Constant Volume (C_v) for 1,1,1,2-Tetrafluoroethane (R134a)**, *International Journal of Refrigeration* (IJR), 15(6):372-380, July 1992 (9 pages with 4 figures and 3 tables, available from JMC as RDB3705)

thermodynamic properties of R-134a; thermophysical data

A. Nagashima, R. Krauss, and K. Stephan (Universität Stuttgart, Germany), **R134a**, in *Transport Properties of Fluids. Their Correlation, Prediction and Estimation*, edited by J. Millat, J. H. Dymond, and C. A. Nieto de Castro, Cambridge University Press, chapter 14.5, 378-387, 1996 (10 pages, rdb9915)

thermal conductivity and viscosity of R-134a; thermophysical data

K. Oguchi and M. Yamagishi (Kanagawa Institute of Technology, Japan), **Study of PVT Properties for HFC-134a**, *Proceedings of the 30th High Pressure Conference* (Sendai, Japan), Japan, 358-359, 1990 (2 pages, rdb9140)

thermodynamic properties of R-134a; thermophysical data

T. Okubo, T. Hasuo, and A. Nagashima, **Measurement of the Viscosity of HFC-134a in the Temperature Range 213-423 K and at Pressure up to 30 MPa**, *International Journal of Thermophysics,* 13(6):931-942, 1992 (12 pages, rdb4882)

R-134a, measurements for -60 to 150 °C (-76 to 302 °F) up to 30 MPa (4350 psia), transport properties, thermophysical data

C. M. B. P. Oliveira and W. A. Wakeham, **The Viscosity of Liquid R134a**, *International Journal of Thermophysics,* 14(1):33-44, 1993 (12 pages, rdb-4A51)

reports new measurements of the viscosity of liquid R-134a for -38 to 70 °C (-37 to 158 °F) and pressures up to 50 MPa (7300 psia) in a vibrating-wire viscometer: estimates the uncertainty as ±0.6%; represents the viscosity data as a function of density by means of a formulation based upon the rigid, hard-sphere theory of dense fluids with a maximum deviation of ±0.3%; this representation allows extrapolation of the data to regions of thermodynamic state not covered by measurements

I. B. Parker, M. H. Barley, and R. W. Wheelhouse (ICI Chemicals and Polymers Limited, UK), **The Reconciling of Diverse Literature Sources of PVT Data on Klea[(R)] 134a**, *Energy Efficiency and Global Warming Impact* (proceedings of the meetings of Commissions B1 and B2, Ghent, Belgium 12-14 May 1993), International Institute of Refrigeration (IIR), Paris, France, 183-190, 1993 (8 pages with 4 figures and 2 tables, RDB5315)

R-134a, thermodynamic properties, thermophysical data, Martin-Hou equation of state (EOS), GFIT correlation

J. Petrak, **Kältemittel R 134a - h,lgp-Diagramm und die Bewertung des einstufigen Kältemittel-Kreisprozesses** [Refrigerant R-134a - Enthalpy-Log-Pressure Diagram and Estimation of the Single-Stage Cycle], *Ki Klima-Kälte-Heizung*, 17(12):556-570, 1989 (15 pages In German, rdb-5214)

R-1 34a, enthalpy-log pressure diagram

C-C. Piao, M. Noguchi (Daikin Industries, Limited, Japan), H. Sato, and K. Watanabe (Keio University, Japan), **An Improved Equation of State for R-134a,** paper 3771, *Transactions* (Winter Meeting, New Orleans, LA, January 1994), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 100(1):358-366, 1994 (9 pages with 16 figures and 1 table, RDB4872)

presents an 18-coefficient, modified Benedict-Webb-Rubin (MBWR) equation of state (EOS) and new correlations of vapor pressure and saturated liquid density for the thermodynamic properties of R-134a: the EOS was developed from measured pressure-volume-temperature (PVT) properties, saturation properties, and isochoric heat capacities by a least-squares fit; experimental data for the isobaric heat capacities, speed of sound, and second virial coefficients also were considered; the equation covers both the superheated vapor and compressed liquid phases at pressures up to 70 MPa (10,000 psia), densities to 1,600 kg/m^3 (100 lb/ft^3), and temperatures from -93 to 227 °C (-135 to 440 °F); the data and correlations are based on the 1990 International Temperature Scale (ITS-90)

C-C. Piao, H. Sato, and K. Watanabe (Keio University, Japan), **Thermodynamic Charts, Tables, and Equations for HFC-134a**, paper 3518, *Transactions* (Annual Meeting, Indianapolis, IN, 22-26 June 1991), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 97(2):268-284, 1991; republished in *Alternative Refrigerants,* technical data bulletin 7(3), ASHRAE, 28-44, October 1991 (17 pages with 15 figures and 4 tables, RDB2615).

R-134a, thermodynamic properties, equation of state (EOS)

Z-Y. Qian, H. Sato, and K. Watanabe (Keio University, Japan), **Compressibility Factors and Virial Coefficients of HFC-134a by a Burnett Apparatus**, *Fluid Phase Equilibria*, 78:323-329, 1992 (7 pages, rdb5464)

R-134a, thermodynamic properties, thermophysical data

M. Ross, J. P. M. Trusler, W. A. Wakeham, and M. Zalaf (Imperial College, UK), **Thermal Conductivity of R-134a over the Temperature Range 240 to 373 K**, *Thermophysical Properties of Pure Substances and Mixtures for Refrigeration* (proceedings of the meeting of IIR Commission B1, Herzlia, Israel, March 1990), International Institute of Refrigeration (IIR), Paris, France, 103-108, 1990 (6 pages with 5 figures and 3 tables, RDB5489)

R-134a, transport properties, thermophysical data, -28 to 212 °F

G. Ya. Ruvinskij, G. K. Lavrenchenko, and S. V. Iljushenko (Institute of Energy Conversion Systems, Ukraine), **Thermophysical Properties of R-134a**, *Kolloidnyi Tekhnika* [Refrigeration Technology], 7:20-26, 1990 (7 pages in Russian, rdb4A42)

thermodynamic data

A. Saitoh, S. Nakagawa, H. Sato, and K. Watanabe (Keio University, Japan), **Isobaric Heat Capacity Data for Liquid HFC-134a**, *Journal of Chemical and Engineering Data*, 35(2):107-110, 1990 (4 pages, rdb4B54)

R-134a, thermodynamic properties, thermophysical data

I. R. Shankland, R. S. Basu, and D. P. Wilson (AlliedSignal Incorporated), **Thermal Conductivity and Viscosity of a New Stratospherically Safe Refrigerant - 1,1,1,2-Tetrafluoroethane (R-134a**), *Status of CFCs - Refrigeration Systems and Refrigerant Properties* (proceedings of the meetings of IIR Commissions B1, B2, E1, and E2, Purdue University, West Lafayette, IN), International Institute of Refrigeration, Paris, France, 305-314, July 1988; republished in *CFCs*: *Time of Transition,* American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE), Atlanta, GA, 117-122, 1989 (9 pages with 6 figures and 2 tables, available from JMC as RDB0516, last page is very faint)

thermophysical properties

K. B. Shubert and J. F. Ely (Colorado School of Mines), **Application of a New Selection Algorithm to the Development of a Wide-Range Equation of State For Refrigerant R-134a**, *International Journal of Thermophysics*, 16(1):101-110, January 1995 (10 pages, rdb8224)

presents a new selection algorithm to develop Helmholtz equations of state (EOS): method combines least-squares regression analysis with simulated annealing optimization; simulated annealing, unlike stepwise regression, allows controlled acceptance of random increases in the objective function; procedure produces a computationally-efficient selection algorithm that is not susceptible to function-space local-minima problems present in a purely stepwise regression approach; compares equations derived with and without the new algorithm against experimental data and other EOSs for R134a

K. Stephan (Universität Stuttgart, Germany), **R134a, Thermodynamic and Physical Properties**, International Institute of Refrigeration (IIR), Paris, France, 1992 (28 pages, rdb9920)

properties of R-134a

S. Tang, G. X. Jin (University of Maryland), and J. V. Sengers (University of Maryland and the National Institute of Standards and Technology, NIST), **Thermodynamic Properties of 1,1,1,2-Tetrafluoroethane (R134a) in the Critical Region**, *International Journal of Thermophysics,* 12(3):515-540, May 1991, with erratum in 16(4):1027-1028, July 1995 (28 pages with 9 figures and 5 tables, RDB7A30)

theoretically based, simplified crossover model to represent the thermodynamic properties of fluids near the critical point: resulting equation of state (EOS) model is applied to R-134a to calculate thermophysical data at 92-177 °C (197-350 °F)

R. Tillner-Roth (Universität Hannover, Germany) and R. Krauss (Universität Stuttgart, Germany), **R134a - Extended Thermophysical Properties,** International Institute of Refrigeration (IIR), Paris, France, 1995 (rdb7A11)

R-1 34a, thermophysical data

R. Tillner-Roth and H. D. Baehr (Universität Hannover, Germany), **An International Standard Formulation of the Thermodynamic Properties of 1,1,1,2-Tetrafluoroethane (HFC-134a) Covering Temperatures from 170 K to 455 K at Pressures up to 70 MPa**, *Journal of Physical and Chemical Reference Data,* 23(5):657-729, 1994 (73 pages, rdb7967)

R-134a, equation of state (EOS), thermodynamic properties, thermophysical data

O. B. Tsvetkov, I. I. Orekhov, and Y. A. Laptev (Saint Petersburg State Academy of Refrigeration

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and Food Technologies, Russia), **Transport Properties of 1,1,1,2-Tetrafluoroethane (R134a) in the Rarified Gas State**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:575-581, 1995 (7 pages with 1 figure and 1 table, rdb7904)

R-134a, thermal conductivity, transport properties, thermophysical data

O. B. Tsvetkov, Y. A. Laptev, and A. G. Asembaev (Saint Petersburg State Academy of Refrigeration and Food Technologies, Russia), **Experimental Study and Correlation of the Thermal Conductivity of 1,1,1,2-Tetrafluoroethane (R134a) in the Rarified Gas State**, *International Journal of Refrigeration* (IJR), 18(6):373-377, July 1995 (5 pages with 1 figure and 3 tables, RDB8262)

thermodynamic properties of R-134a; thermophysical data

A. van Pelt, G. X. Jin (University of Maryland), and J. V. Sengers (University of Maryland and National Institute of Standards and Technology, NIST), **Critical Scaling Laws and a Classical Equation of State**, *International Journal of Thermophysics,* 15(4):687-697, July 1994 (11 pages with 3 figures, RDB6402)

method to modify a classical equation of state (EOS) by incorporating nonclassical critical behavior, illustrated by application to the Carnahan-Starling-DeSantis (CSD) EOS, gives parameters and constants for renormalized CSD equation for R-134 and compares the results to published experimental data

E. T. Vas'kov, **Equation of State and Thermodynamic Properties of 1,1,1,2-Tetrafiuoroethane**, *Inzhenerno-Fizicheskii Zhurnal* [Journal of Engineering Physics], Minsk, Belarus (then USSR), 68(1):66-70, January 1995 (5 pages probably in Russian, rdb7C02)

presents pressure, density, temperature, and heat capacity data for R-134a along with a derived virial equation of state (EOS) and a set of equations to determine thermodynamic properties for the vapor and liquids phases; also presents calculated property tables for saturated and superheated R-134a for -53 to 227 °C (-64 to 440 °F) and 0.01-7.5 MPa (1.5-1088 psia)

J. Wilhelm and E. Vogel (Universität Rostock, Germany), **Gas Phase Viscosity of the Alternative Refrigerant R134a at Low Densities**, *Proceedings of the Fourth Asian Thermophysical Properties Conference* (Tokyo, Japan, 5-8 September 1995), 1995 (rdb8906)

transport properties for R-134a; thermophysical data

L. A. Weber (National Institute of Standards and Technology, NIST), **Vapor Pressures and Gas-Phase PVT Data for 1,1,1,2-Tetrafluoroethane**, *International Journal of Thermophysics,* 10(3):617-627, May 1989 (12 pages with 3 figures and 4 tables, RDB0909)

New data for the vapor pressure and PVT surface of R-134a in the temperature range of 40-150 °C (104-302 °F) are presented. The PVT data are for the gas phase at densities up to one-half critical. Densities of the saturated vapor are derived at five temperatures from the intersections of the experimental isochores with the vapor pressure curve. The data are represented analytically, in order to demonstrate experimental precision and to facilitate calculation of thermodynamic properties. The paper describes and schematically shows the Burnett apparatus, filling system, and pressure measuring system used to obtain the data. It identifies the chief impurities as R-125, R-143a, R-1122, and water, each present at approximately 100 ppm. The paper presents the raw data, equations used to fit the data, and a plot of deviations from the fit; previously published data are over laid for comparison.

D. P. Wilson and R. S. Basu (AlliedSignal Incorporated), **Thermodynamic Properties of a New Stratospherically Safe Working Fluid - Refrigerant 134a**, paper OT-88-20-4, *Transactions* (Annual Meeting, Ottawa, Ontario, Canada, 25-29 June 1988), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 94(2):2095-2118, 1988; republished in *CFCs: Time of Transition,* ASHRAE, 104-116, 1989 (13 pages with 6 figures and 6 tables, RDB2236)

R-134a

V. V. Zhidkov (NORD Association, Ukraine), V. P. Zhelezny, and P. V. Zhelezny (Odessa State Academy of Refrigeration, Ukraine), **Phase Equilibrium in Oil-Refrigerant Solution R-134a/SW22,** *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 447-451, July 1996 (5 pages with no figures or tables, RDB6C25)

pressure, temperature, and concentration relations for refrigerant-lubricant mixtures; thermodynamic properties of R-134a/oil mixtures; possibly R-134a with a branched acid polyolester (Castrol Icematic(R) SW22); thermophysical data

M-S. Zhu, L-Z. Han, Y-D. Fu, J. Wu, and C-X. Lu (Tsinghua University, China), **Research on PVT Properties, Vapor Pressure, and Surface Ten**

sion of HFC-134a, *Proceedings of the 1992 International Refrigeration Conference - Energy Efficiency and New Refrigerants*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 2:499-509, July 1992 (11 pages with 5 figures and 8 tables, available from JMC as RDB2833)

thermodynamic properties of R-134a; thermophysical data

M-S. Zhu, L-Z. Han, and W. Zhou (Tsinghua University, China), **Experimental Research of Surface Tension for HFC-134a**, *Journal of Engineering Thermophysics*, China, 13(1):16-18, 1992 (3 pages in Chinese, rdb8C22)

transport properties of R-134a; thermophysical data

M-S. Zhu, J. Wu, and Y-D. Fu (Tsinghua University, China), **New Experimental Vapor Pressure Data and a New Vapor Pressure Equation for HFC134a,** *Fluid Phase Equilibria*, 80:99-105, 1992 (7 pages with 2 figures and 4 tables, RDB4B41)

measurements of the vapor pressure of R-134a for 6-90 °C (43-194 °F); evaluates published data from other studies and combines the new data with selected old data to develop a consistent data set and a four-coefficient Wagner equation; indicates that the equation of represents the measured data with an accuracy of 0.05350%

Forane(R) 134a, technical digest, Elf Atochem North America, Incorporated, Philadelphia, PA, undated circa 1994 (4 pages with 4 tables, available from JMC as RDB4768)

This bulletin supplies information on R-134a in traditional R-12 applications and as a component for blends targeted for R-22 and R-502 applications. It compares the physical and environmental properties of R-12 and R-134a, and provides a tabular data summary for the latter in inch-pound (IP) units. The table lists the chemical formula, molecular weight, normal boiling and freezing points, heat of vaporization, vapor and liquid density at the boiling point and 27 °C (80 °F), critical parameters (temperature, pressure, and density), specific heat of the liquid at the same temperature and of the vapor at atmospheric pressure, Workplace Environmental Exposure Level (WEEL), ozone depletion potential (ODP), and halocarbon global warming potential (HGWP). The table also shows R-134a to be nonflammable. A second table gives the saturated vapor pressures of R-12 and R-134a for -46 to 93 °C (-50 to 200 °F). A third presents the saturated vapor pressure and liquid and vapor densities and enthalpies for the same temperature range. The document briefly reviews the performance and lubricant considerations of R-134a for climate control and refrigeration. It notes immiscibility with mineral oils, but polyolester and polyalkylene glycol lubricants have been recommended by various equipment manufacturers. The bulletin then discusses retrofitting centrifugal chillers, automotive air conditioners, and refrigeration systems with R-134a. The digest concludes with container identification for R-134a and other alternative refrigerants. Elf Atochem's product name for R-134a is Forane® 134a.

Genetron(R) 134a Product Brochure, bulletin G-525-009, AlliedSignal Incorporated, Morristown, NJ, May 1994 and September 1996 (14 pages with 5 figures and 7 tables, RDB6B26)

This bulletin supplies information on R-134a and application data in metric (SI) and inch-pound (IP) units. R-134a is described as a replacement for R-12 in automobile air conditioning; residential and commercial refrigeration; residential, commercial, and industrial air conditioning including centrifugal chillers; and as a blowing agent and aerosol propellant. The bulletin describes these applications and lists basic physical properties including the chemical name and formula, appearance, molecular weight, normal boiling and freezing points, and critical parameters (temperature, pressure, density, and specific volume). The property data also include the vapor density, latent heat of vaporization at the boiling point, flammability limits (none), auto ignition temperature, ozone depletion potential (ODP), and halocarbon global warming potential (HGWP). Representative data are provided for 25 °C (77 °F) including the liquid density; vapor pressure; solubility in and of water; and vapor and liquid heat capacity, thermal conductivity, and viscosity. The bulletin provides Mollier (pressure-enthalpy) charts, product purity specifications, a tabular comparison of performance with R-12, and tabular pressure-temperature data for -45 to 70 °C (-60 to 160 °F). It then discusses lubricant suitability with primary focus on polyalkylene glycol (PAG) and polyolester (POE) synthetics. Characteristic miscibility plots are shown. The document discusses copper plating with PAG and POE lubricants. It notes that plating levels are lower for R-134a with the cited lubricants than with R-12 and mineral oil. While plating does not appear in laboratory tests with two POEs (Castrol Icematic® SW32 and Mobil EAL Arctic® 22), field occurrence suggests that it may result in the presence of other materials. The bulletin tabulates stability data for the same POEs in the presence of aluminum, copper, and steel. It discusses the effects of chlorinated solvents and residual refrigerants, noting that R-134a is chemically compatible with chlorinated materials, but that the associated PAG and POE lubri-

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cants may not be. It notes, however, that R-12 and R-134a form a higher-pressure azeotrope. The bulletin then discusses materials compatibility and provides tabular, qualitative indications for elastomers and plastics. It discusses suitability with polyethylene terephthalate (PET) and desiccants, and also provides a plot of solubility of water in R-134a. The bulletin then discusses safety, including both toxicity and flammability. It describes the former as intrinsically low. While it suggests that R-134a is nonflammable, it notes that R-134a can become combustible at higher pressures when mixed with more than 60% v/v air. The bulletin discusses storage, handling, safety guidelines, and leak detection methods. It briefly outlines environmental considerations, reclamation, retrofit procedures for R-12 equipment, and R-134a packaging. AlliedSignal's product name for R-134a is Genetron(R) 134a.

Refrigerant Reclin(R) 134a, product bulletin AFK2322e(035), Hoechst Aktiengesellschaft, Frankfurt am Main, Germany, April 1994 (12 pages with 6 figures and 4 tables, RDB4776)

This bulletin provides data for R-134a, identified as a substitute for R-12, in refrigeration engineering, in metric (SI) units of measure. The introduction reviews the phaseout of chlorine-containing refrigerants and criteria for substitutes. A table summarizes physical and thermodynamic property data for R-134a, including the chemical formula and name, molecular mass, normal boiling and freezing points, and critical parameters (temperature, pressure, and density). It also gives the heat of vaporization, surface tension, liquid density, isentropic exponent, solubility of water, solubility in water, dynamic viscosity, and thermal conductivity at selected conditions. The bulletin reviews thermodynamic similarities of R-134a with R-12. Four plots compare their compression ratios, compressor discharge temperatures, volumetric refrigerating effect, and coefficient of performance for suction temperatures of -30 to 5 °C (-22 to 41 °F). The bulletin then discusses compatibility with metals, recommending avoidance only of zinc, magnesium, lead, and aluminum alloys with more than 2% magnesium. It reports storage tests that showed good stability to hydrolysis and no corrosive attack on ferritic steel, V2A steel, copper, brass, and aluminum. The bulletin provides elastomer swell, extraction, and elongation data for R-134a with butyl (IIR), acrylonitrile-butadiene (NBR, Perbunan(R)), hydrogenated nitrile butadiene rubber (HNBR), chloroprene (CR, Neoprene(R)), fluorinated (FPM, DuPont Viton(R) A), natural (NR), and ethylene propylene diene terpolymer (EPDM) rubbers. It notes suitability with polytetrafluoroethylene (PTFE, Hostaflon(R)), polyacetal (POM, Hostaform(R)), and polyamide (PA) thermoplastics, but cautions that lubricant influences also must be considered. R-134a is indicated as almost completely immiscible with conventional mineral oils and also with some synthetics lubricants such as alkylbenzenes. The bulletin discusses miscibility and considerations for polyalkylene glycol (PAG) and polyolester (POE) lubricants as well as consequences of residual paraffinic or naphthenic oils from retrofit or manufacturing. A plot shows conceptual mixing ranges for polyglycols and esters with R-134a. The bulletin reports that both R-134a and R-12 pass the Philipp test for thermal stability with mineral oil, and that the stability of R-134a appears to be better than that of R-12. The bulletin indicates that R-134a does not form flammable mixtures with air under normal conditions, but that flammable mixtures can form above atmospheric pressure if the air fraction exceeds 60%. It warns that mixtures of R-134a with air or oxygen must never be used for leak or pressure tests. It notes that R-134a has been found to be at least as safe as R-12 toxicologically and recommends a workplace exposure limit of 1000 ppm by volume on an eight-hour, time-weighted average basis. A table provides thermodynamic property data including pressure; liquid and vapor specific volumes, densities, enthalpies, and entropies; and the heat of vaporization. These data cover R-134a at saturated (wet vapor) conditions from -60 to the critical point of 101.15 °C (-76 to 214.07 °F). The bulletin concludes with a pressure-enthalpy (Mollier) diagram based on a U.K. Rombusch equation of state. Hoechst Chemical's product name for R-134a is Hoechst Reclin® 134a.

Thermodynamic Properties of HFC-134a (1,1,1,2-tetrafluoroethane), technical information report T-134a-ENG (H-47751), DuPont Chemicals, Wilmington, DE, January 1993 (36 pages with 1 figure and 2 tables, available from JMC as RDB3426)

This report provides thermodynamic property data for R-134a in inch-pound (IP) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a modified Benedict-Webb-Rubin (MBWR) equation of state and an ideal gas heat capacity equation at constant pressure. It also gives a Martin-Hou (MH) equation of state (EOS), fit from MBWR data, and a corresponding ideal gas heat capacity equation at constant vapor. It supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (pressure and liquid and vapor volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -101 to 101 °C (-150 to 213 °F). A set of tables presents volume, enthalpy, entropy, heat capacity at constant pressure, heat capacity ratio (dimensionless Cp/Cv), and velocity of sound data for superheated vapor at constant pressure for 7-3800 kPa (1-550 psia). The new tables are based on experimental data from the National Institute of Standards and Technology, NIST). The report concludes with a pressure-enthalpy diagram. DuPont's product names for R-134a are Suva(R) 134a Refrigerant, Suva(R) Cold-MP Refrigerant, Suva(R) Trans-AC Refrigerant, Formacel(R) Z-4 Blowing Agent, Dymel(R) 134a Aerosol Propellant, and Dymel(R) 134a/P Aerosol Propellant.

Thermodynamic Properties of HFC-134a (1,1,1,2-tetrafluoroethane), technical information report T-134a-SI (H-47752), DuPont Chemicals, Wilmington, DE, January 1993 (36 pages with 1 figure and 2 tables, available from JMC as RDB3427)

This report provides thermodynamic property data for R-134a in metric (SI) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a modified Benedict-Webb-Rubin (MBWR) equation of state and an ideal gas heat capacity equation at constant pressure. It also gives a Martin-Hou (MH) equation of state (EOS), fit from MBWR data, and a corresponding ideal gas heat capacity equation at constant vapor. It supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (pressure and liquid and vapor volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -100 to 101 °C (-148 to 213 °F). A set of tables presents volume, enthalpy, entropy, heat capacity at constant pressure, heat capacity ratio (dimensionless Cp/Cv), and velocity of sound data for superheated vapor at constant pressure for 10-4000 kPa (1-580 psia). The new tables are based on experimental data from the National Institute of Standards and Technology, NIST). The report concludes with a pressure-enthalpy diagram. DuPont's product names for R-134a are Suva(R) 134a Refrigerant, Suva(R) Cold-MP Refrigerant, Suva(R) Trans-AC Refrigerant, Formacel(R) Z-4 Blowing Agent, Dymel(R) 134a Aerosol Propellant, and Dymel(R) 134a/P Aerosol Propellant.

Thermodynamic Properties of Klea® 134a, British Units, bulletin 620250011, ICI Klea, Wilmington, DE, March 1995 (48 pages with 2 tables, RDB6302)

This bulletin provides detailed thermodynamic properties for saturated and superheated R-134a in inch-pound (IP) units of measure. It comprises two tables. The first presents saturation properties by temperature (°F and °R) for -101 to 100 °C (-150 to 212 °F) and at the critical point, 101 °C (213.80 °F). The tabular data include absolute and gauge pressure; liquid and vapor specific volume, density, enthalpy, and entropy; and the latent heat of vaporization. The second table provides volume, enthalpy, and entropy data for superheated vapor at constant pressure. The data span the range of 14-3790 kPa (2-550 psia) to temperatures as high as 159 °C (318 °F). ICI's product name for R134a is Klea(R) 134a.

Thermodynamic Properties of Klea 134a, SI Units, bulletin CP/34421/30371/4ED/33/394, ICI Klea, Runcorn, Cheshire, UK, March 1994 (64 pages with 2 tables, RDB6B29)

This bulletin provides detailed thermodynamic properties for saturated and superheated R-134a in metric (SI) units of measure. It comprises two tables. The first presents saturation properties by temperature (°C and K) for -80 to 101 °C (-112 to 214 °F) and at the critical point, 101 °C (213.8 °F). The tabular data include absolute pressure; liquid and vapor specific volume, density, enthalpy, and entropy; and the latent heat of vaporization. The second table provides volume, enthalpy, and entropy data for superheated vapor at constant pressure. The data span the range of 20-4000 kPa (3-580 psia) to temperatures as high as 218 °C (424 °F). ICI's product name for R-134a is Klea(R) 134a.

R-141b

D. Arnaud, S. Macaudiere, L. Niveau, and S. Wosinski (Atochem Groups ELF Aquitaine, France), **Propriétés Thermophysiques d'un Nouveau Fluids Frigorigéne: le 1,1-Dichloro-1-fluoroéthane (HFA-141b)** [Thermophysical Properties of a New Refrigerant: 1,1-Dichloro-1-fluoroethane (HCFC-141b)], paper 71, *New Challenges in Refrigeration* (proceedings of the XVIIIth International Congress of Refrigeration, Montreal, Québec, Canada, 10-17 August 1991), International Institute of Refrigeration (IIR), Paris, France, August 1991 (rdb7715)

R-141b, thermodynamic properties, thermophysical data as reported in RDB 7713

D. R. Defibaugh, A. R. H. Goodwin, G. Morrison, and L. A. Weber (National Institute of Standards and Technology, NIST), **Thermodynamic Properties of 1,1-Dichloro-1-fluoroethane (R141b),** *Fluid*

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Phase Equilibria, 85:271-284, 1993 (13 pages with 8 figures and 5 tables, RDB4909)

thermodynamic properties of R-141b: presents measurements of compressed liquid densities using a vibrating-tube densimeter for 5-96 °C (41-205 °F) and 100-6,000 kPa (14.5-870 psia); also presents vapor pressure measurements with comparative and sapphire ebulliometers for -20 to 82 °C (-4 to 179 °F) and 10-449 kPa (1.5-65 psia); provides correlations of the data and comparisons to published studies by other researchers; thermophysical data

A. R. H. Goodwin and M. R. Moldover (National Institute of Standards and Technology, NIST), **Thermophysical Properties of Gaseous Refrigerants from Speed of Sound Measurements: II. Results for 1,1-Dichloro-1-fluoroethane (CCl_2FCH_3)**, *Journal of Chemical Physics*, 95(7):5230-5235, 1 October 1991 (6 pages with 5 figures and 4 tables, RDB3105)

thermodynamic properties of R-141b; thermophysical data

R. Malhotra and L. A. Woolf (Australian National University, Australia), **Volumetric Measurements for 1,1-Dichloro-1-fluoroethane (R141b) in the Temperature Range 278.15 to 338.15 K and Pressure Range from 0.1 to 380 MPa**, *Fluid Phase Equilibria,* 92:195-213, 15 January 1994 (19 pages, rdb8936)

measurements of pVT data for R-141b in the form of volume ratios using a an automated bellows volumometer to obtain for pressures up to 380 MPa (55,000 psia) in the temperature range 5-65 °C (41-149 °F) in the liquid phase: the accuracy of the volume ratios is estimated to be ±0.05-0.1% for the experimental temperatures up to 5 °C (41 °F) and better than ±0.15% for temperatures above the normal boiling point of R-141b; the volume ratios enable accurate predictions of liquid densities along the liquid-vapor coexistence boundary and evaluation of the isothermal compressibilities, isobaric expansivities, internal pressures, and isobaric molar heat capacities

L. A. Weber (National Institute of Standards and Technology, NIST), **PVT and Thermodynamic Properties of R141b in the Gas Phase,** paper 69, *New Challenges in Refrigeration* (proceedings of the XVIIIth International Congress of Refrigeration, Montreal, Québec, Canada, 10-17 August 1991), International Institute of Refrigeration (IIR), Paris, France, 11:616-625, August 1991 (12 pages with 4 figures and 5 tables, available from JMC as RDB-3615)

R-141 b, equation of state (EOS), thermophysical properties

Genetron(R) 141b Bulletin, document B-525-647, AlliedSignal Incorporated, Morristown, NJ, October 1993 (4 pages with 4 figures and 7 tables, RDB5A29)

This bulletin supplies information and application data on R-141b in inch-pound (IP) units. R-141b is described as a replacement for R-11 as a blowing agent, for insulation in construction, appliance, and vehicle applications. A table lists data including the appearance, odor, chemical formula, molecular weight, and normal boiling and freezing points. The properties listed include the specific gravity; vapor pressure, density, and thermal conductivity; liquid density; and solubility in and of water at or near 25 °C (77 °F). The bulletin also lists the autoignition temperature, flash point (none), and lower and upper flame limits (LFL and UFL). It briefly mentions compatibility with plastics including polytetrafluoroethylene (PTFE), polyethylene, polypropylene, polyvinylidene fluoride, and phenolic coatings. It also addresses elastomers including perfluoroelastomers, but notes unsatisfactory results with nitrile rubber, ethylene propylene rubber, and neoprene. The bulletin compares the flame limits measured by several test methods, and compares the findings to those for R-30, R-140a, and R-1120. It then tabulates the vapor pressure, vapor thermal conductivity, liquid viscosity, and liquid density of R-141b at temperatures between -18 and 93 °C (0 and 200 °F). These data are plotted with corresponding curves for R-11 for comparison. AlliedSignal's product name for R-141b is Genetron(R) 141b.

Genetron(R) 141b Bulletin, document B-525-647-SIU, AlliedSignal Incorporated, Morristown, NJ, October 1993 (4 pages with 7 tables, RDB5A30)

This bulletin supplies information and application data on R-141b in metric (SI) units. R-141b is described as a replacement for R-11 as a blowing agent, for insulation in construction, appliance, and vehicle applications. A table lists data including the appearance, odor, chemical formula, molecular weight, and normal boiling and freezing points. The properties listed include the specific gravity; vapor pressure, density, and thermal conductivity; liquid density; and solubility in and of water at or near 25 °C (77 °F). The bulletin also lists the autoignition temperature, flash point (none), and lower and upper flame limits (LFL and UFL). It briefly mentions compatibility with plastics including polytetrafluoroethylene (PTFE), polyethylene, polypropylene, polyvinylidene fluoride, and phenolic coatings. It also addresses elastomers including perfluoroelastomers, but notes unsatisfactory results with nitrile rubber, ethylene propylene rubber, and neoprene. The bulletin compares the flame limits measured by several test methods, and compares the findings to those for R-30, R-140a, and R-1120. It then tabulates the vapor pressure, vapor thermal conductivity, liquid viscosity, and liquid density of R-141b at temperatures between -10 and 90 °C (14 and 194 °F). AlliedSignal's product name for R-141b is Genetron(R) 141b.

Genetron(R) 141b Product Brochure, bulletin B-525-648, AlliedSignal Incorporated, Morristown, NJ, November 1993 (6 pages with 5 tables, RDB5A33)

This bulletin supplies information and application data on R-141b in metric (SI) and inch-pound (IP) units. R-141b is described as an Interim replacement for R-11 as a blowing agent, for use in rigid polyurethane foams. The bulletin summarizes these applications and then outlines safety implications. It briefly reviews toxicity testing for R-141b and recommended permissible exposure limits (PEL consistent and WEEL) of 500 ppm. It discusses flammability, compares the flame limits by several test methods, and compares the findings to those for R30, R-140a, and R-1120. The discussion notes that while R-141b is flammable, it does not exhibit either an open- or closed-cup flash point and is not considered a flammable liquid for transportation. The bulletin discusses environmental aspects of R-141b use including its low ozone depletion potential (ODP) and disposal of wastes. It then reviews stability and compatibility data, and gives tabular test results (weight, hardness, and volume change) for polymers. The plastics include polyvinyl chloride (PVC), polyethylene, polypropylene polyvinylidene fluoride (Elf Atochem Kynar(R)), vinylester (Dow Chemical Derekane(R) 411), and polyphenylene sulfide (Phillips Petroleum Ryton(R) R-7). The elastomers include DuPont Kalrez(R) and Viton(R) E60C, nitrile, neoprene, silicone, urethane, butyl rubber, and ethylene propylene rubber. The bulletin then addresses reactivity with emphasis on finely divided metals, storage, handling, and safety precautions for equipment maintenance. It lists product specifications and tabulates representative properties including the chemical name and formula, appearance, molecular weight, and normal boiling and freezing points. The property data also include the vapor density, flammability limit, and autoignition temperature. Representative data are provided at or near 25 °C (77°F) including the liquid density, vapor pressure, specific gravity, and solubility in and of water. AlliedSignal's product name for R-141b is Genetron(R) 141b.

R-142b

L. I. Cherneeva, **Experimental Investigation of the Thermodynamic Properties of Fluorochemical 142**, *Teploenergetica* [Thermoenergetics], 1958(7):-38-43, 1958 (6 pages in Russian, RDB7C45)

thermodynamic properties of R-142b; thermophysical data

K. Kumagai, N. Yada, H. Sato, and K. Watanabe (Keio University, Japan), **A Study of PVT Properties of HCFC-142b**, *Proceedings of the Tenth Japan Symposium on Thermophysical Properties* (20-22 September 1989), Shizuoka University, Japan, 67-70, 1989 (4 pages, rdb4224)

thermodynamic properties of R-142b; thermophysical data

Y. Maezawa, H. Sato, and K. Watanabe (Keio University, Japan), **Liquid Densities and Vapor Pressures of 1-Chloro-1,1-difluoroethane (HCFC-142b)**, *Journal of Chemical and Engineering Data*, 36:148-150, 1991 (5 pages, rdb5468)

thermodynamic properties of R-142b; thermophysical data

Y. Maezawa, H. Sato, and K. Watanabe (Keio University, Japan), **Saturated Liquid Densities of HCFC-142b**, *Proceedings of the Tenth Japan Symposium on Thermophysical Properties* (20-22 September 1989), Shizuoka University, Japan, 71-74, 1989 (4 pages, rdb4227)

thermodynamic properties of R-142b; thermophysical data

S. Nakagawa, H. Sato, and K. Watanabe (Keio University, Japan), **Measurement of Isobaric Heat Capacity of Liquid HCFC-142b**, *Proceedings of the Eleventh Japan Symposium on Thermophysical Properties*, 103-106, 1990 (4 pages, rdb3930)

thermodynamic properties of R-142b; thermophysical data

S. Tanikawa, Y. Kabata, H. Sato, and K. Watanabe (Keio University, Japan), **Measurements of the Critical Parameters and the Vapor-Liquid Coexistence Curve and Critical Parameters of 1-Chloro-1,1-difluoroethane (HCFC-142b)**, *Journal of Chemical and Engineering Data*, 37:74-76, 1992 (3 pages, rdb5466)

thermodynamic properties of R-142b; thermophysical data

N. Yada, K. Kumagai, T. Tamatsu, H. Sato, and K. Watanabe (Keio University, Japan), **Measurements of the Thermodynamic Properties of HCFC-142b**, *Journal of Chemical and Engineering Data,* 36:12-14, 1991 (3 pages, rdb5477)

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thermodynamic properties of R-142b; thermophysical data

Genetron(R) 142b, technical bulletin B-525-649, AlliedSignal Incorporated, Morristown, NJ, September 1993 (4 pages with 3 tables, RDB3A58)

This bulletin supplies information on R-142b, described as a replacement for R-12 in rigid polyurethane, polystyrene, and polyethylene foam insulation applications for residential and commercial construction as well as process piping. It provides physical property data, in inch-pound (IP) units, including the chemical formula, molecular weight, atmospheric boiling and freezing points and vapor density, flash point, and autoignition temperature. It also indicates the specific gravity and vapor pressure at 21 °C (70 °F) and the vapor thermal conductivity and liquid density at 25 °C (77 °F). It briefly outlines materials interactions citing compatibility with carbon steel, stainless steel, phenolic coatings, polytetrafluoroethylene (PTFE), fluoroelastomer, polyethylene (PE), polypropylene, and polyvinylidenefluoride. The bulletin notes unsatisfactory results with nitrile rubber, ethylene propylene rubber, and neoprene. It then presents flammability information, including a comparison with pentane. It concludes with tabular and plotted vapor pressure, vapor thermal conductivity, liquid viscosity, and liquid density data. AlliedSignal's product name for R-142b is Genetron(R) 142b.

R-143

C. D. Holcomb and L. J. Van Poolen (National Institute of Standards and Technology, NIST), **Coexisting Densities and Vapor Pressures for R143 from 314 to 401 K with new Critical Point Property Estimates**, *Fluid Phase Equilibria,* 100:223-239, 1994 (7 pages with 11 figures and 4 tables, RDB-8247)

presents measured thermodynamic properties of R-143 for 41-128 °C (106-262 °F); compares them to data for R-143a; estimates the critical point as 156.65 °C (313.97 °F), 5.241 MPa (760.1 psia), and 469 kg/m^3 (29.3 lb/ft^3); fits the data to Carnahan-Starling-DeSantis (CSD) and Dieters equations of state (EOS); compares the findings to published data from other studies; thermophysical data

R-143a

D. Arnaud, S. Macaudiere, L. Niveau, and S. Wosinski (Atochem Groupe ELF Aquitaine, France), **Propriétés Thermophysiques d'un Nouveau Fluide Frigorigène: le 1,1,1-Trifluoroéthane (HFA-143a)** [Thermophysical Properties of a New Refrigerant: 1,1,1-Trifluoroethane (HFA-143a)], paper 79, *New Challenges in Refrigeration* (proceedings of the XVIIIth International Congress of Refrigeration, Montreal, Québec, Canada, 10-17 August 1991), International Institute of Refrigeration (IIR), Paris, France, 11:664-668, August 1991 (5 pages with 3 figures and 6 tables, RDB4A39)

R-143a, thermodynamic properties, thermophysical data

M. Fukushima (Keio University, Japan), **Measurements of Vapor Pressure, Vapor-Liquid Coexistence Curve, and Critical Parameters of HFC-143a**, *Nippon Reito Kyokai Ronbunshu* [Transactions of the JAR], Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 10:87-93, 1993 (7 pages in Japanese, rdb8252)

thermodynamic properties of R-143a, thermophysical data

G. Giuliani, S. Kumar, P. Zazzini, and F. Polonara (Università degli Studi di Ancona, Italy), **Vapor Pressure and Gas-Phase Data and Correlation for 1,1,1-Trifluoroethane**, *Journal of Chemical and Engineering Data,* 40:903-908, 1995 (6 pages, rdb8257)

thermodynamic properties of R-143a; pressure-temperature relations; thermophysical data

S. L. Outcalt and M. O. McLinden (National Institute of Standards and Technology, NIST), **An Equation of State for the Thermodynamic Properties of R143a (1,1,1-Trifluoroethane)**, *International Journal of Thermophysics,* 18(6):1445-1463, November 1997 (17 pages with 15 figures and 6 tables, RDB8301)

modified Benedict-Webb-Rubin (MBWR) equation of state (EOS) for R-143a: provides coefficients for a 32-term MBWR equation and ancillary equations to calculate the ideal-gas heat capacity and the coexisting densities and pressure along the saturation boundary; MBWR coefficients were determined with a multiproperty fit to measured data including pressure-volume-temperature (PVT) dependence, heat capacities (isochoric, isobaric, and saturated liquid), second virial coefficients, speed of sound, and properties at coexistence; the equation of state accurately represent experimental data from -111 to 73 °C (-168 to 163 °F) and pressures to 35 MPa (5,100 psia) with the exception of the critical region; equation gives reasonable results for extrapolations to 227 °C (440 °F) and 60 MPa (8,700 psia)

C-C. Piao, K. Fujiwara, and M. Noguchi (Daikin Industries, Limited, Japan), **Thermodynamic Properties of HFC-143a (1,1,1-Trifluoroethane)**, *Fluid Phase Equilibria,* 150-151:303-312, 1998 (8 pages with 9 figures and 5 tables, RDB8C24)

identifies prior property studies and presents an 18-coefficient modified Benedict-Webb-Rubin (MBWR) equation of state (EOS) for R-143a; indicates that the EOS is valid for superheated vapors and compressed liquid phases from the triple point at -111.81 °C (-169.26 °F) to 160 °C (320 °F) and pressures up to 35 MPa (5100 psia); presents correlations for the ideal gas heat capacity, vapor pressure, and saturated liquid density; compares calculated properties to experimental data; thermophysical data

H. Russell, D. R. V. Golding, and D. M. Yost, **The Heat Capacity, Heats of Transition, Fusion and Vaporization, Vapor Pressure and Entropy of 1,1,1-trifluoroethane**, *Journal of the American Chemical Society*, 66:16-20, 1944 (5 pages, rdb-4317)

thermodynamic properties of R-143a; thermophysical data

H. Wang, Z. Li, Y. Ma, and C. Lu, **Experimental Study on Vapor Pressure and Critical Parameters of CH_3CF_3**, *Huagong Xuebao* [Journal of Chemical Industry and Engineering], China, 44:373-377, 1993 (5 pages, rdb8260)

thermodynamic properties of R-143a; thermophysical data

H. Wang, Y. Ma, C. Lu, and Y. Tian, *Beijing Gongchang Rewuli Xuebao* [Beijing Journal of Engineering Thermophysics], Beijing, China, 14:124 ff, 1993 (rdb8303)

thermodynamic properties of R-143a; thermophysical data

L. A. Weber and D. R. Defibaugh (National Institute of Standards and Technology, NIST), **Vapor Pressures and PVT Properties of the Gas-Phase of 1,1,1-Trifluoroethane**; *Journal of Chemical and Engineering Data,* 41(6):1477-1480, 1996 (4 pages with 4 figures and 4 tables, RDB8205)

thermodynamic properties of R-143a; measurements of the gas-phase pressure-volume-temperature (PVT) surface for 3-100 °C (37-212 °F) and pressures up to 6.6 MPa (957 psia) using a Burnett isochoric PVT apparatus; measurements of vapor pressures for -37 to 70 °C (-35 to 158 °F) using a metal ebulliometer; formulations for the second and third virial coefficients; equation for the vapor pressure curve; thermophysical data

H-L. Zhang, H. Sato, and K. Watanabe (Keio University, Japan), **Vapor Pressures, Gas-Phase PVT Properties, and Second Virial Coefficients for 1,1,1-Trifluoroethane**, *Journal of Chemical and Engineering Data,* 40:887-890, 1995 (4 pages, rdb-8258)

thermodynamic properties of R-143a; pressure-volume-temperature relations; second virial coefficients; thermophysical data

R-152a

W. Blanke and R. Weiß, **Isochoric (pVT) Measurements on $C_2H_4F_2$ (R152a) in the Liquid State from the Triple Point to 450 K and at Pressures up to 30 MPa**, *Preprints of the 11th Symposium on Thermophysical Properties* (Boulder, CO, 23-27 June 1991), American Society of Mechanical Engineers (ASME), New York, NY, 1991; republished in *Fluid Phase Equilibria,* 80(11):179-190, 1992 (12 pages, rdb4555)

thermodynamic data for R-152a from the triple point to 177 °C (350 °F) and pressures up to 30 MPa (4350 psia)

D. R. Defibaugh and G. Morrison (National Institute of Standards and Technology, NIST), **Compressed Liquid Densities, Saturated Liquid Densities, and Vapor Pressures of 1,1-Difluoroethane**, *Journal of Chemical and Engineering Data,* 41(3):376-381, 1992 (6 pages with 6 figures and 3 tables, RDB8239)

thermodynamic properties of R-152a: measurements of the liquid densities using a vibrating-tube densimeter for -30 to 98 °C (-22 to 208 °F) and pressures from near the saturated vapor pressure to 6.5 MPa (943 psia), approaching the critical point; measurements of vapor pressures using an ebulliometer for 7-273 °C (44-524 °F); calculations of the saturated liquid densities by extrapolating the compressed liquid isotherms to the saturation pressure; thermophysical data

Y. Higashi, M. Ashizawa, Y. Kabata, T. Majima, M. Uematsu, and K. Watanabe (Keio University, Japan), **Measurements of Vapor Pressure, Vapor-Liquid Coexistence Curve, and Critical Parameters of Refrigerant 152a**, *JSME International Journal (series II: Fluids Engineering, Heat Transfer, Power, Combustion, and Thermophysical Properties*), Japan Society of Mechanical Engineers (JSME), Tokyo, Japan, 30(265):1106-1112, 1987 (7 pages In English, available from ASME in

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the Americas and from Maruzen Company, Limited, elsewhere, rdb4121)

R-152a, thermodynamic properties, thermophysical data

T. Hozumi, I. Furutsuka, H. Sato, and K. Watanabe (Keio University, Japan), **Sound Velocity Measurements in Gaseous HFC-152a**, *Proceedings of the Third Asian Thermophysical Properties Conference* (Beijing, People's Republic of China), 258-363, 1992 (6 pages, rdb5480)

R-152a, physical data

A. Iso and M. Uematsu (Keio University, Japan), **Thermodynamic Properties of 1,1-Difluoroethane in the Super-Critical and High Density Regions**, *Physica A*, 156:454-466, 1989 (13 pages, rdb4A53)

thermodynamic properties of R-152a; thermophysical data

R. Krauss (Universität Stuttgart, Germany), V. C. Weiss (University of Maryland, USA, and Universität Bremen, Germany), T. A. Edison, J. V. Sengers (University of Maryland, USA), and K. Stephan (Universität Stuttgart, Germany), **Transport Properties of 1,1-Difluoroethane (R152a)**, *International Journal of Thermophysics,* 17(4):731-757, July 1996 (27 pages with 12 figures and 8 tables, RDB6408)

equations for the thermal conductivity and viscosity of R-152a for -33 to 167 °C (-28 to 332 °F) including the critical region; thermophysical data

R. Krauss and K. Stephan (Universität Stuttgart, Germany), **Neue Korrelationen für die Viskosität und Wärmeleitfähigkeit von R152a** [New Correlations for the Viscosity and Thermal Conductivity of R-152a], *Bericht über die Kälte-Klima-Tagung* [Proceedings of the Refrigeration and Air-Conditioning Conference] (Ulm, Germany, 1995), Deutscher Kälte- und Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, 231-245, 1995 (15 pages, in German, RDB9913)

correlations for the thermal conductivity and viscosity of R-152a; transport properties; thermophysical data

R. Krauss and K. Stephan (Universität Stuttgart, Germany), **Viskosität und Wärmeleitfähigkeit des alternativen Kältemittels 1,1-Difluorethan (R152a)** [Viscosity and Thermal Conductivity of Alternative Refrigerant 1,1-Difluoroethane (R-152a)], *Bericht über die Kälte-Klima-Tagung* [Proceedings of the Refrigeration and Air-Conditioning Conference] (Bonn, Germany, 1994), Deutscher Kälte- und Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, 159-172, 1994 (14 pages, in German, rdb9912)

thermal conductivity and viscosity of R-152a; transport properties; thermophysical data

R. Krauss and K. Stephan (Universität Stuttgart, Germany), **Transport Properties of 1,1-Difluoroethane (R152a)**, *Preprints of the 12th Thermophysical Properties Symposium* (Boulder, CO, 19-24 June 1994), American Society of Mechanical Engineers (ASME), New York, NY, June 1994; republished in *CFCs, the Day After* (proceedings of the IIR meeting, Padova, Italy, 21-23 September 1994), International Institute of Refrigeration (IIR), Paris, France, 363-373, September 1994 (11 pages, rdb9911)

transport properties of R-152a; thermophysical data

N. I. Lapardin, **The Viscosity of Difluoroethane**, *Neft i Gaz*, 25:24-63, 1982 (in Russian, rdb8909)

transport properties of R-152a; viscosity; thermophysical data

T. Majima, M. Uematsu, and K. Watanabe (Keio University, Japan), **Measurements of PVT Properties of Refrigerant 152a**, *Proceedings of the Eighth Japan Symposium on Thermophysical Properties*, 77-81, 1987 (5 pages, rdb4225)

thermodynamic properties of R-152a; thermophysical data

S. L. Outcalt and M. O. McLinden (National Institute of Standards and Technology, NIST), **A Modified Benedict-Webb-Rubin Equation of State for the Thermodynamic Properties of R152a (1,1-Difluoroethane)**, *Journal of Physical and Chemical Reference Data*, 25:, 1996 (rdb8908)

modified, 32-term, Benedict-Webb-Rubin (MBWR) equation of state (EOS) for R-152a: The EOS is based on experimental property data including single-phase pressure-volume-temperature (PVT), heat capacity, and speed of sound data as well as the second virial coefficient, vapor pressure, and saturated liquid and saturated vapor density. The paper presents coefficients for both the EOS and ancillary equations for the vapor pressure, saturated liquid and saturated vapor densities, and the ideal gas heat capacity. Experimental data used in this work covered temperatures from -111 to -180 °C (-168 to 356 °F) and pressures to 35 MPa (5100 psia): The MBWR equation established in this work may be used to predict thermodynamic properties of R152a from the triple-point temperature of -118.59 to 227 °C (-181.46 to 440 °F) and for pressures up to 60 MPa (8700 psia) except in the immediate vicinity of the critical point.

Z-Y. Qian, T. Majima, H. Sato, and K. Watanabe (Keio University, Japan), **Preliminary Determination of Virial Coefficients for HFC-152a**, *Proceedings of the Third Asian Thermophysical Properties Conference* (Beijing, People's Republic of China), 346-351, 1992 (6 pages, rdb5463)

thermodynamic properties of R-152a; thermophysical data

T. Tamatsu, T. Sato, H. Sato, and K. Watanabe (Keio University, Japan), **An Experimental Study of Thermodynamic Properties of 1,1-Difluoroethane**, *International Journal of Thermophysics,* 13:985-997, 1992 (13 pages, rdb8266)

thermodynamic properties of R-152a; thermophysical data

M. Uematsu, H. Sato, and K. Watanabe (Keio University, Japan), **Saturated Liquid Density of 1,1-Difluoroethane (R152a) and Thermodynamic Properties Along the Vapor-Liquid Coexistence Curve**, *Fluid Phase Equilibria,* 36:167-181, 1987 (15 pages, rdb4122)

thermodynamic properties of R-152a; thermophysical data

P. S. van der Gulik, **Viscosity of Saturated R152a Measured with a Vibrating Wire Viscometer**, *International Journal of Thermophysics,* 16:867-876, 1995 (10 pages, rdb8951)

transport properties of R-152a; thermophysical data

P. S. van der Gulik, **The Viscosity of Refrigerant 1,1-Difluoroethane Along the Saturation Line**, *International Journal of Thermophysics,* 14(4):851-864, 1993 (14 pages, rdb7836)

transport properties of R-152a; thermophysical data

A. van Pelt and J. V. Sengers (University of Maryland), **Thermodynamic Properties of 1,1-Difluoroethane (R152a) in the Critical Region**, *Journal of Supercritical Fluids,* 8:81-99, 1995 (19 pages with 16 figures and 4 tables, RDB6403)

R-152a, theoretically-based crossover model to adapt a classical, analytic equation of state (EOS) in the critical region, gives parameters and constants for the crossover model for R-152a, summary of experimental data sets and calculated thermodynamic property data for R-152a

J. M. Yin, J. X. Guo, Z. Y. Zhao, L-C. Tan, and M. Zhao (Xi'an Jiaotong University, China), **Thermal Conductivity of HFC-152a**, *Fluid Phase Equilibria,* 80:297-303, 1992 (7 pages, rdb4B55)

R-152a, thermophysical properties

Z. Y. Zhao, J. M. Yin, and L-C. Tan (Xi'an Jiaotong University, China), **Measurement of PVT Properties and Vapor Pressure for HFC-152a**, *Preprints of the 11th Symposium on Thermophysical Properties* (Boulder, CO, 23-27 June 1991), American Society of Mechanical Engineers (ASME), New York, NY, 1991; republished in *Fluid Phase Equilibria,* 80:191-202, 1992 (12 pages, rdb4B56)

R-152a, thermodynamic properties, thermophysical data

R-170(Ethane)

D. E. Diller and J. M. Saber (National Bureau of Standards, NBS, now the National Institute of Standards and Technology, NIST), **Measurements of the Viscosity of Compressed Gaseous and Liquid Ethane**, *Physica A*, 108A:143 ff, 1981 (rdb8305)

transport properties of R-170 (ethane): measurement of the viscosity; thermophysical data

D. R. Douslin and R. H. Harrison, **Pressure, Volume, and Temperature Relations of Ethane**, *Journal of Chemical Thermodynamics*, 5:491 ff, 1973 (rdb8C38)

thermodynamic properties of R-170 (ethane): PVT, thermophysical data

D. G. Friend, H. Ingham, and J. F. Ely, **Thermophysical Properties of Ethane**, *Journal of Physical and Chemical Reference Data*, 20(2):122-187 (possibly 275-347), 1991 (65 OR 73 pages, rdb-7973)

thermodynamic properties of R-170 (ethane): thermophysical data

R. D. Goodwin, H. M. Roder, and G. C. Straty, **Thermodynamic Properties of Ethane from 90 to 600 K at Pressures to 700 Bar**, NBS Technical Note 684, National Institute of Standards and Technology (NIST, then the National Bureau of Standards, NBS), Gaithersburg, MD, August 1976 (available from GPO, rdb3944)

R-170, equation of state (EOS), thermophysical data

R. Hahn, K. Schafer, and B. Schramm, **Messungen zweiter Virialkoeffizienten im Temperaturbereich von 200-300 K** [Measurements of the Second Virial Coefficient in the Temperature Range of 200-300

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K], *Berichte der Bunsengesellschaft für Physikalische Chemie,* 78:287 ff, 1974 (rdb8C39)

thermodynamic properties of R-170 (ethane): second virial coefficient for -73 to 27 °C (-100 to 80 °F); thermophysical data

H. Hendl, J. Millat, E. Vogel, V. Vesovic, W. A. Wakeham, and (Imperial College, UK), J. Luettmer-Strathmann, J. V. Sengers (University of Maryland), and M. J. Assael (Aristotle University, Greece) **The Transport Properties of Ethane. I. Viscosity**, *International Journal of Thermophysics,* 15(1):1-31, 1994 (31 pages, rdb9903)

viscosity of R-170 (ethane); transport properties; thermophysical data

V. Vesovic, W. A. Wakeham (Imperial College, UK), J. Luettmer-Strathmann, J. V. Sengers (University of Maryland), J. Millat, E. Vogel, and M. J. Assael (Aristotle University, Greece) **The Transport Properties of Ethane. II. Thermal Conductivity**, *International Journal of Thermophysics,* 15(1):33-66, 1994 (34 pages, rdb9904)

thermal conductivity of R-170 (ethane); transport properties; thermophysical data

R-227ea

L. Shi, Y-Y. Duan, M-S. Zhu, L-Z. Han (Tsinghua University, China), and X. Lei (Beijing United University, China), **Vapor Pressure of 1,1,1,2,3,3,3-Heptafluoropropane,** *Fluid Phase Equilibria,* 163:-109-117, 1999 (9 pages with 6 figures and 1 table, RDB9711)

determination of the normal boiling point (NBP) and measurements of the vapor pressure of R-227ea for -30 to 102 °C (-22 to 215 °F): presents the modified Burnett apparatus used, 84 raw data points, and a Wagner correlation for them

R-236fa

S. L. Outcalt and M. O. McLinden (National Institute of Standards and Technology, NIST), **An Equation of State for the Thermodynamic Properties of R236fa**, report for contract N61533-94-F-0152, U.S. Navy, David Taylor Research Center, Annapolis, MD, 1995 (Rdb8915)

presents a modified Benedict-Webb-Rubin (MBWR) equation of state (EOS) for R-236fa: provides coefficients for a 32-term MBWR EOS and for ancillary equations to calculate the vapor pressure, saturated vapor and liquid densities, and ideal-gas heat capacity; describes predictions from an extended corresponding states (ECS) model for regions lacking data; examination of calculated properties indicate that the EOS gives reasonable extrapolation down to the triple point at -93 °C (-136 °F) and up to 227 °C (440 °F) and 40 MPa (5,800 psia)

Hydrofluorocarbons HFG-3236 (R236fa), product bulletin 98-0211-8554-5(HB), 3M Specialty Chemicals Division, Saint Paul, MN, October 1996 (4 pages with 1 figure and 4 tables, available from JMC as RDB6B05)

R-236fa identified as a replacement for R-114 in centrifugal chillers and in high-temperature heat pump and cooling systems; notes planned use by the U.S. Navy in chillers on ships; gives the chemical formula and name, molecular weight, environmental properties, normal boiling point, critical parameters (temperature, pressure, and density), and the saturated liquid and vapor density and specific heat as well as the latent heat of vaporization at the boiling point; lists product specifications; cites an unreferenced study that shows R-236fa with an unidentified polyolester (POE) outperformed R-114 with mineral oil for miscibility, lubricity, stability, and metals and non-metals compatibility; discusses safety and handling; provides a table of thermodynamic properties and a pressure enthalpy chart in inch-pound units of measure

R-245ca

D. R. Defibaugh, K. A. Gillis, M. R. Moldover, J. W. Schmidt, and L. A. Weber (National Institute of Standards and Technology, NIST), **Thermodynamic Properties of CHF_2-CF_2-CH_2F, 1,1,2,2,3-Pentafluoropropane**, *International Journal of Refrigeration* (IJR), 19(4):285-294, May 1996 (10 pages with 5 figures and 5 tables, RDB8214)

R-245ca, CH_2F-CF_2-CHF_2, thermodynamic properties, thermophysical data, coefficients for a Carnahan-Starling-DeSantis (CSD) equation of state (EOS)

N. D. Smith, **Thermophysical Properties of HFC-245ca,** Environmental Research Brief EPA-600/S-92-038, U.S. Environmental Protection Agency (EPA), Research Triangle Park, NC, August 1992 (4 pages with 5 tables, available from JMC as RDB-3402)

This synopsis summarizes properties of R-245ca (1,1,2,2,3-pentafluoropropane), a potential alternative for R-11 and R-123. It notes that the thermophysical properties of the fluids closely match, and that modeling indicates acceptable performance. The efficiency of R-245ca is indicated as 3-4% less than R-11 and 1-2% less than R-123. Tables, in both inch-pound (IP) and metric (SI) units provide the melting and boiling points, critical properties, heat of vaporization, and liquid heat capacity. Measured liquid densities are given at six temperatures from 22-140 °C (72-284 °F) and vapor pressures for -39 to 26 °C (-38 to 78 °F). Calculated liquid and vapor density as well as vapor pressure and heat of vaporization are tabulated for 5-178 °C (41-353 °F) and the equations used are provided. The ideal gas heat capacity is similarly provided for 27-327 °C (80-620 °F). The methods used and estimated accuracy are indicated.

R-245cb

R. L. Shank (Union Carbide Corporation), **Thermodynamic Properties** of **1,1,1,2,2-Pentafluoropropane (Refrigerant 245cb)**, *Journal of Chemical and Engineering Data*, 12(4):474-480, October 1967 (7 pages with 4 figures and 5 tables, rdb2506)

Thermodynamic properties are presented for the saturated liquid and vapor of R-245cb from -40 °C (-40 °F) to the critical temperature, 106.96 °C (224.52 °F); a pressure-enthalpy diagram Is included. The critical properties, coefficients for a Benedict-Webb-Rubin (BWR) equation of state (EOS), a vapor-pressure equation, a liquid-density equation, and a heat-capacity equation are given. Data also are provided for the superheated vapor from the saturation temperature to 371 °C (700 °F). The properties listed are volume, enthalpy, entropy, heat capacity at constant pressure, and heat capacity ratio as functions of temperature and pressure. Pressure-volume isotherms are plotted for both the high-density and critical regions. These properties were calculated from measured volumetric and spectral data; the experimental procedures and calculations are described.

L. A. Weber and D. R. Defibaugh (National Institute of Standards and Technology, NIST), **Vapor Pressure of 1,1,1,2,2-Pentafluoropropane**, *Journal of Chemical and Engineering Data*, 41(4):762-764, 1996 (3 pages with 1 figure and 2 tables, RDB8215)

measurements of the thermodynamic properties of R-245cb for -199 to 53 °C (-326 to 127 °F) and 74-995 kPa (11-144 psia), thermophysical data

R-245fa

R. R. Singh, H. M. Hughes, H. Magid, M. W. Spatz, and D. P. Wilson (AlliedSignal Incorporated), **HFC-245fa, A Chiller Refrigerant,** *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 26-33, November 1997 (6 pages with 3 tables, RDB8324)

thermodynamic properties of R-245fa: briefly reviews the search for replacements for R-11 and R-123 and the flammability and environmental characteristics of R-245fa; compares the performance of R-245fa to R-11, R-123, and R-134a; presents a Martin-Hou (MH) equation of state (EOS) and correlations for the vapor pressure, liquid density, and ideal gas heat capacity of R-245fa; concludes that R-245fa shows considerable promise as a refrigerant in centrifugal chillers at a small increase in pressure and without significant decrease in efficiency; notes that R-245fa could extend the range of low-pressure chillers to higher capacities

HFC-245fa, bulletin G525-513, AlliedSignal Incorporated, Morristown, NJ, October 1996 (2 pages with 3 figures and 1 table, RDB6B20)

This preliminary bulletin introduces R-245fa as a potential replacement for R-141b and other chemicals. It is being developed for use as a blowing agent for rigid insulating foams. The preliminary bulletin presents selected data for R-245fa, described as a nonflammable liquid having a boiling point slightly below room temperature. A table lists physical properties including the molecular formula and weight, boiling point, and water solubility. It indicates the liquid density and vapor pressure at 20 °C (68 °F) and the vapor thermal conductivity at 40 °C (104 °F). It also states that R-245fa exhibits neither a flash point nor flame limits, based on identified tests. A discussion of toxicity notes that R-245fa is not currently listed on the U.S. EPA TSCA, European INEX, or Japanese MITI inventories, and therefore is classified as a research material that may not be used commercially. While a Permissible Exposure Limit (PEL) has been set, the bulletin cites tests that indicate R-245fa to have low toxicity by both dermal and inhalation routes of exposure. The bulletin reports tests that demonstrate no mutagenic activity in an *in vivo* micronucleus study and an Ames assay, and only weak activity in an *in vitro* cytogenetics test. A cardiac sensitization study was negative at concentrations up to 20,000 ppm v/v. Plots show the pressure-temperature relation and miscibility in polyether polyols (BASF Pluracol(R) 824 and 975, Dow Chemical Voranol(R) 390, Bayer Corporation Multranol(R) 4063, and

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Eastman Chemical Thanol(R) 470X) as well as aromatic polyester polyols (Hoechst Celanese Terate(R) 203, 254, and 2541 and Oxid Terol(R) 235). The bulletin briefly reviews the environmental benefits of the hydrofluorocarbon (HFC) and outlines laboratory stability tests, which showed high thermal and hydrolytic stability. It then indicates that compatibility tests are underway, with favorable results to date for neoprene, EPDM, nylon polytetrafluoroethylene (PTFE, DuPont Teflon(R)), HIPS, and ABS. It suggests unfavorable findings for fluoroelastomers, nitrile, and HNBR. The bulletin concludes with recommendations for storage and handling.

R-C270

H. S. Booth and W. C. Morris, **The Critical Constants and Vapor Pressure of Cyclopropane**, *Journal of Physical Chemistry*, 62:875-876, 1958 (2 pages, rdb7C55)

R-C270, thermodynamic properties, thermophysical data

D. C. Lin, I. H. Silberberg, and J. J. McKetta, **Thermodynamic Properties of Cyclopropane**, *Journal of Chemical and Engineering Data*, 16(4):416-418, 1971 (3 pages, rdb7C52)

R-C270, thermodynamic properties, thermophysical data

D. C. Lin, I. H. Silberberg, and J. J. McKetta, **Volumetric Behavior, Vapor Pressures, and Critical Properties of Cyclopropane**, *Journal of Chemical and Engineering Data*, 15(4):483-492, 1970 (10 pages, rdb7C53)

R-C270, thermodynamic properties, thermophysical data

R. A. Ruehrwein and T. M. Powell, **The Heat Capacity, Vapor Pressure, Heats of Fusion and Vaporization of Cyclopropane, Entropy and Density of the Gas**, *Journal of the American Chemical Society*, 68:1063-1066, 1946 (4 pages, rdb7C54)

R-C270, thermodynamic properties, thermophysical data

R-290 (Propane)

J. F. Ely and R. Kobayashi, **Isochoric Pressure-Volume-Temperature Measurements for Compressed Liquid Propane**, *Journal of Physical and Chemical Reference Data*, 23:221 ff, 1978 (rdb8240)

thermodynamic properties of R-290, thermophysical data, hydrocarbons

N. S. Ersova, E. B. Petrunina, and A. V. Kleckij, **Equation of State and Thermodynamic Properties of Propan**e, *Kolloidnyi Tekhnika* [Refrigeration Technology], 1:30-33, 1981 (4 pages in Russian, rdb5710)

R-290, thermophysical data

R. D. Goodwin, **Provisional Thermodynamic Functions of Propane from 85 to 700 K at Pressures to 700 Bar**, report NBSIR 77-860, National Institute of Standards and Technology (NIST, then the National Bureau of Standards, NBS), Gaithersburg, MD, July 1977 (available from GPO, rdb3945)

R-290, thermophysical properties, equation of state (EOS)

W. M. Haynes (National Institute of Standards and Technology, NIST), **Measurements of Densities and Dielectric Constants of Liquid Propane from 90 to 300 K at Pressures to 35 MPa**, *Journal of Chemical Thermodynamics*, 15:419 ff, 1983 (rdb8248)

thermodynamic and transport properties of R-290 for -183 to -27 (-298 to 80 °F) and pressures up to 35 MPa (5076 psia); thermophysical data

R. H. P. Thomas and R. H. Harrison (Bartlesville Energy Technology Center), **Pressure-Volume-Temperature Relations of Propane**, *Journal of Chemical and Engineering Data*, 27(1):1-11, 1982 (11 pages, rdb5718)

thermodynamic properties of R-290, thermophysical data

H. Reamer, B. H. Sage, and W. N. Lacey, **Phase Equilibria in Hydrocarbon Systems: Volumetric Behavior of Propane**, *Industrial and Engineering Chemistry*, 41:482 ff, 1949 (rdb8249)

thermodynamic properties or R-290, thermophysical data

E. T. Vaskov, **Thermodynamic Properties of Propane at Saturation State**, *Inzhenerno-Fizicheskii Zhurnal* [Journal of Engineering Physics], Moscow, Russia (then USSR), 46(2):272-275, 1984 (4 pages in Russian, rdb5719)

R-290, thermophysical data

E. Vogel (Universität Rostock, Germany), **The Viscosity of Gaseous Propane and Its Initial Density Dependence**, *International Journal of Thermophysics*, 16:1335-1351, 1995 (17 pages, rdb8905) transport properties for R-290; thermophysical data

R-C318

G. Bambach (Technische Universität Karlsruhe, Germany) **Octofluorocyclobutane C_4F_8**, *Kältetechnik*, Germany, 8(1):334-339, 1956 (6 pages in German, rdb4117)

R-C318 (octafluorocyclobutane), thermophysical properties, toxicity (suggests linkage to delayed deaths to animals exposed at 760,000 ppm as reported and discussed in RDB5A25)

R. Cipollone (University of L'Aquila, Italy), **Thermodynamic Properties of Perfluorocyclobutane (C_4F_8)**, paper 3517, *Transactions* (Annual Meeting, Indianapolis, IN, 22-26 June 1991), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 97(2), 1991; republished in *Alternative Refrigerants*, technical data bulletin 7(3); ASHRAE, 45-50, October 1991 (6 pages with 8 figures and 4 tables, RDB4116)

R-C318 (octafluorocyclobutane), thermophysical data

J. J. Martin (University of Michigan), **Thermodynamic Properties of Perfluoroclyclobutane**, *Journal of Chemical and Engineering Data*, 7:68 ff, January 1962 (rdb7A51)

R-C318 (octafluorocyclobutane), thermodynamic properties, thermophysical data

H. Matthias and H. F. Löffler, **Thermodynamische Eigenschaften von Octofluorcyclobutan (C_4F_8)** [Thermodynamic Properties of Octofluorocyclobutane], *Kältetechnik,* Germany, 6:240-241, 1966 (2 pages in German, rdb4118)

R-C318 (octafluorocyclobutane), thermophysical data

R-338qcc

D. R. Defibaugh, J. J. Hurly, M. R. Moldover, J. W. Schmidt, L. A. Weber, and E. Carrillo-Nava (National Institute of Standards and Technology, NIST), **Thermodynamic Properties of HFC-338mccq CF_3-CF_2-CF_2-CH_2F, 1,1,1,2,2,3,3,4-Octafluorobutane**, *Journal of Chemical and Engineering Data*, 42(3):488-496, 1997 (9 pages with 6 figures and 9 tables, RDB8212)

R-338mcc, CH_2F-CF_2-CF_2-CF_3, thermophysical data

R-400

H. H. Kruse, M. Küver, U. Quast, M. Schroeder, and B. Upmeier (Universität Hannover, Germany), **Theoretical and Experimental Investigations of Advantageous Refrigerant Mixture Applications**, *Transactions* (Annual Meeting, Honolulu, HI, 23-26 June 1985), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 91(2B):1383-1418, 1985; republished in *Advances in Nonazeotroplc Mixture Refrigerants for Heat Pumps*, technical data bulletin 1(9), ASHRAE, 96-131, 1985 (36 pages with 8 figures and 8 tables, RDB2351)

R-12, R-114; vapor-liquid equilibria (VLE) data for R-400 (R-12/114), R-22/114, and R-13/12; R-13B1 /114

R-401A

Thermodynamic Properties of Suva(R) MP39 Refrigerant [R-401 (53/13/34)], technical information report T-MP39-ENG (H-47764), DuPont Chemicals, Wilmington, DE, January 1993 (28 pages with 1 figure and 2 tables, available from JMC as RDB3430)

This report provides thermodynamic property data for R-401A, a blend of R-22, R-152a, and R-124 - R-22/152a/124 (53/13/34) - in inch-pound (IP) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -101 to 99 °C (-150 to 211 °F). A set of tables presents volume, enthalpy, and entropy data for superheated vapor at constant pressure for 7-3800 kPa (1-550 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-401A Is Suva(R) MP39.

Thermodynamic Properties of Suva(R) MP39 Refrigerant [R-401 (53/13/34)], technical information report T-MP39-SI (H-47765), DuPont Chemicals, Wilmington, DE, January 1993 (24 pages with 1 figure and 2 tables, available from JMC as RDB3431)

This report provides thermodynamic property data for R-401A, a blend of R-22, R-152a, and R-

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124 - R-22/152a/124 (53/13/34) - in metric (SI) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng--Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -100 to 99 °C (-148 to 210 °F). A set of tables presents volume, enthalpy, and entropy data for superheated vapor at constant pressure for 10-3800 kPa (1-550 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-401A Is Suva® MP39.

R-401B

Thermodynamic Properties of Suva(R) MP66 Refrigerant [R-401 (61/11/28)], technical information report T-MP66-ENG (H-47759), DuPont Chemicals, Wilmington, DE, January 1993 (24 pages with 1 figure and 2 tables, available from JMC as RDB3432)

This report provides thermodynamic property data for R-401B, a blend of R-22, R-152a, and R124 - R-22/152a/124 (61 /11 /28) - in inch-pound (IP) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -101 to 97 °C (-150 to 207 °F). A set of tables presents volume, enthalpy, and entropy data for superheated vapor at constant pressure for 7-3800 kPa (1-550 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-401B is Suva(R) MP66.

Thermodynamic Properties of Suva® MP66 Refrigerant [R-401 (61/11/28)], technical information report T-MP66-SI (H-47760), DuPont Chemicals, Wilmington, DE, January 1993 (24 pages with 1 figure and 2 tables, available from JMC as RDB3433)

This report provides thermodynamic property data for R-401B, a blend of R-22, R-152a, and R-124 - R-22/152a/124 (61 /11 /28), in metric (SI) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -100 to 97 °C (-148 to 207 °F). A set of tables presents volume, enthalpy, and entropy data for superheated vapor at constant pressure for 10-4000 kPa (1-580 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-401B is Suva(R) MP66.

R-401C

Thermodynamic Properties of Suva(R) MP52 Refrigerant [R-401 (33/15/52)], technical information report T-MP52-ENG (H-47769), DuPont Chemicals, Wilmington, DE, February 1993 (28 pages with 1 figure and 2 tables, available from JMC as RDB3428)

This report provides thermodynamic property data for R-401C, a blend of R-22, R-152a, and R124 - R-22/152a/124 (33/15/52) - in inch-pound IP) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -101 to 104 °C (-150 to 220 °F). A set of tables presents volume, enthalpy, and entropy data for superheated vapor at constant pressure for 7-3800 kPa (1-550 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-401C is Suva(R) MP52.

Thermodynamic Properties of Suva(R) MP52 Refrigerant [R-401 (33/15/52)], technical information report T-MP52-SI (H-47770), DuPont Chemicals, Wilmington, DE. February 1993 (24 pages with 1 figure and 2 tables, available from JMC as RDB3429)

This report provides thermodynamic property data for R-401C, a blend of R-22, R-152a, and R-124 - R-22/152a/124 (33/15/52) - in metric (SI) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -100 to 104 °C (-148 to 220 °F). A set of tables presents volume, enthalpy, and entropy data for superheated vapor at constant pressure for 10-4000 kPa (1-580 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-401C is Suva(R) MP52.

R-402A

Thermodynamic Properties of Suva(R) HP80 Refrigerant [R-402 (60/2/38)], technical information report T-HP80-ENG (H-47766), DuPont Chemicals, Wilmington, DE, January 1993 (24 pages with 1 figure and 2 tables, available from JMC as RDB3436)

This report provides thermodynamic property data for R-402A, a blend of R-125, R-290, and R-22 - R-125/290/22 (60/2/38) - in inch-pound (IP) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -101 to 68 °C (-150 to 154 °F). A set of tables presents volume, enthalpy, and entropy data for superheated vapor at constant pressure for 7-3800 kPa (1-550 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-402A is Suva(R) HP80.

Thermodynamic Properties of Suva(R) HP80 Refrigerant [R-402 (60/2/38)], technical information report T-HP80-SI (H-47767), DuPont Chemicals, Wilmington, DE, January 1993 (24 pages with 1 figure and 2 tables, available from JMC as RDB3437)

This report provides thermodynamic property data for R-402A, a blend of R-125, R-290, and R-22 - R-125/290/22 (60/2/38) - in metric (SI) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -100 to 68 °C (-148 to 154 °F). A set of tables presents volume, enthalpy, and entropy data for superheated vapor at constant pressure for 10-4000 kPa (1-580 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-402A is Suva(R) HP80.

R-402B

Thermodynamic Properties of Suva(R) HP81 Refrigerant [R-402 (38/2/60)], technical information report T-HP81-ENG (H-47757), DuPont Chemicals, Wilmington, DE, January 1993 (24 pages with 1 figure and 2 tables, available from JMC as RDB3434)

This report provides thermodynamic property data for R-402B, a blend of R-125, R-290, and R-22 - R-125/290/22 (38/2/60) - in inch-pound (IP) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -101 to 75 °C (-150 to 167 °F). A set of tables presents volume, enthalpy, and entropy data for superheated vapor at constant pressure for 7-3800 kPa (1-550 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-402B Is Suva(R) HP81.

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Thermodynamic Properties of Suva(R) HP81 Refrigerant [R-402 (38/2/60)], technical information report T-HP81-SI (H-47758), DuPont Chemicals, Wilmington, DE, January 1993 (20 pages with 1 figure and 2 tables, available from JMC as RDB3435)

This report provides thermodynamic property data for R-402B, a blend of R-125, R-290, and R-22 - R-125/290/22 (38/2/60) - in metric (SI) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -100 to 74 °C (-148 to 165 °F). A set of tables presents volume, enthalpy, and entropy data for superheated vapor at constant pressure for 10-4000 kPa (1-580 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-402B is Suva(R) HP81.

R-403B

Isceon 69-L, information packet, National Refrigerants, Incorporated, Philadelphia, PA, March 1992 (16 pages containing 1 figure and 5 tables, RDB3A64)

This set of documents includes physical, thermodynamic, and application data on R-403B, a ternary zeotropic blend of R-22, R-218, and R-290 (propane) formulated as R-290/22/218 (5/56/39). This alternative refrigerant is targeted as a "drop-in" replacement for R-502 in existing refrigeration systems. The packet provides physical property data and saturated vapor pressures, the latter from -62 to 57 °C (-80 to 135 °F), in inch-pound units. It also includes thermodynamic property (pressure, specific volume, density, enthalpy, and entropy as functions of temperature) tables for saturated conditions, from -50 to 89 °C (-58 to 192 °F), and for superheated vapor in metric (SI) units. A pressure-enthalpy diagram, in SI units, is provided. The information packet gives general guidelines for retrofit of R-502 systems to use the blend, a retrofit checklist, and a theoretical performance comparison for the two fluids. Rhône-Poulenc Chemical's product name for R-4038 Is Isceon 69-L; National Refrigerants is the exclusive distributor for North America.

R-404A

Forane(R) 404A, technical digest, Elf Atochem North America, Incorporated, Philadelphia, PA, undated circa 1994 (4 pages with 4 tables, available from JMC as RDB4769)

This bulletin supplies information on R-404A, a near-azeotropic blend of R-125, R-143a, and R-134a - R-125/143a/134a (44/52/4). R-404A was formulated to closely match the properties of R-502 for use in medium and low temperature refrigeration in both new systems and applications. A table provides physical and environmental property data for R-404A in inch-pound (IP) units. The table lists the chemical formulation, average molecular weight, normal boiling point, heat of vaporization, vapor and liquid density at the boiling point and 25 °C (77 °F), critical parameters (temperature, pressure, and density), specific heat of the liquid at the same temperature and of the vapor at atmospheric pressure, maximum temperature glide, ozone depletion potential (ODP), and halocarbon global warming potential (HGWP). The table also shows R-404A to be nonflammable at test temperatures up to 100 °C (212 °F). A second table gives the saturated vapor pressures of R-404A and R-502 for -51 to 54 °C (-60 to 130 °F). A third presents the bubble and dew point temperatures and the liquid and vapor densities and enthalpies for R-404A for pressures of 34-2760 kPa (5-400 psia). The document briefly discusses considerations for use of near-azeotropic blends with attention to temperature glide, composition changes, and charging implications. It also reviews performance, lubrication, and materials compatibility considerations for R-404A for new and retrofit systems. It notes immiscibility with mineral oils and the need for their replacement with polyolester lubricant. It also points out that pressure relief devices may need modification due to the higher operating pressures of R-404A compared to R-502. The digest concludes with container identification for R-404A and other alternative refrigerants. Elf Atochem identified R-404A as FX-70 for research and development; its product name for the blend is Forane(R) 404A.

Genetron(R) 404A, technical bulletin B-525-532, AlliedSignal Incorporated, Morristown, NJ, April 1995 (4 pages with 2 tables, RDB6102)

This bulletin supplies information on R-404A, described as a replacement for refrigerants 22 and 502 in low- and medium-temperature, commercial refrigeration applications. The document notes that R-404A is not a "drop in" because a polyolester (POE) lubricant should be used, for miscibility. It also advises that this refrigerant be charged with liquid refrigerant, since vapor charging could result in the wrong composition. The bulletin presents physical property data, in inch-pound (IP) units, including the composition, molecular weight, normal boiling point, corresponding heat of vaporization, critical parameters (temperature, pressure, and density), flammability, and ozone depletion potential. It also indicates the liquid density and specific heats of the liquid and vapor at 30 °C (86 °F). The report provides tabular thermodynamic properties (bubble- and dew-point pressure, liquid density, vapor volume, liquid and vapor enthalpy and entropy, and latent heat of vaporization) for -46 to 71 °C (-50 to 160 °F). AlliedSignal's product name for R-404A is Genetron(R) 404A.

Kältemittel Reclin(R) 404A [Refrigerant Reclin(R) 404A], product bulletin AF2634d, Hoechst Aktiengesellschaft, Frankfurt am Main, Germany, May 1994 (28 pages with 6 figures and 7 tables, in German, RDB4777)

This bulletin provides data for R-404A, identified as a near-azeotropic blend of R-125, R-143a, and R-134a - R-125/143a/134a (44/52/4), in metric (SI) units of measure. The blend is described as a substitute for R-22 and R-502 in low-temperature refrigeration. The introduction reviews the phaseout of chlorine-containing refrigerants and criteria for substitutes. A table summarizes physical and thermodynamic property data for R-404A, including the chemical formulation and name, molecular mass, normal boiling point, freezing range, and critical parameters (temperature, pressure, and density). It also gives the heat of vaporization, liquid and vapor density, specific heat, isentropic exponent, flammability limits (none), thermal conductivity, and dynamic viscosity at selected conditions. The bulletin reviews thermodynamic similarities of R-404A with R-22 and R-502. Four plots compare their compression ratios, compressor discharge temperatures, volumetric refrigerating effect, and coefficient of performance for evaporating temperatures of -45 to -5 °C (-49 to 23 °F). The bulletin then discusses compatibility with metals, recommending avoidance of zinc, magnesium, lead, and aluminum alloys with more than 2% magnesium. It reports storage tests that showed good stability to hydrolysis and no corrosive attack on cast iron, refined steel, copper, brass, and aluminum. The bulletin provides changes in Shore hardness, elastomer swell, extraction, and elongation data for R-404A with ethylene propylene diene terpolymer (EPDM), fluorinated (FKM), hydrogenated nitrile butadiene rubber (HNBR), acrylonitrile-butadiene (NBR), and chloroprene (CR) rubbers. It notes suitability with polytetrafluoroethylene (PTFE, Hostaflon(R)), polyacetal (POM, Hostaform(R)), and polyamide (PA) thermoplastics, but cautions that lubricant influences also must be considered. R-404A is indicated as almost completely immiscible with conventional mineral oils and also with some synthetics lubricants such as alkylbenzenes. The bulletin discusses miscibility and considerations for polyalkylene glycol (PAG) and polyolester (POE) lubricants. A plot shows miscibility of R-404A with an ester lubricant (Fuchs Reniso E 32). The bulletin reports that the absence of chlorine atoms in hydrofluorocarbon (HFC) refrigerants leads to higher thermal stability. The bulletin outlines toxicity testing for R-125 and R-134a, and that recommended exposure limits of 1000 ppm have been set for R-125, R-134a, and R-143a (the components of R404A), but that exposures should still be kept to a minimum. It also notes that R-134a does not form flammable mixtures with air under normal conditions, but that flammable mixtures can form above atmospheric pressure if the air fraction exceeds 60%. R-143a is indicated as flammable, but R-125 is not. The blend does not burn, even after fractionation by leakage. The bulletin warns that mixtures of R-404A with air or oxygen must never be used for leak or pressure tests. The bulletin discusses leakage, noting that even losses up to 70% by mass have small impacts and that the blend performs nearly the same way, as an azeotrope. It also discusses recycling and notes that Hoechst will accept used R-404A for reclaim. Two tables provide thermodynamic property data. The first includes bubble and dew point pressures; liquid and vapor specific volumes, densities, enthalpies, and entropies; and the heat of vaporization. These data cover R-404A at saturated (wet vapor) conditions from -60 to 65 °C (-76 to 149 °F). The second provides specific volume, enthalpy, and entropy data for the superheated vapor from -50 to 200 °C (-58 to 392 °F). The bulletin concludes with a pressure-enthalpy (Mollier) diagram based on a Peng-Robinson-Stryjek-Vera (PRSV) equation of state. Hoechst Chemical's product name for R-404A is Reclin(R) 404A.

Thermodynamic Properties of Suva(R) HP62 Refrigerant [R-404A (44/52/4)], technical information report T-HP62-ENG (H-49744-1), DuPont Chemicals, Wilmington, DE, December 1993 (24 pages with 1 figure and 2 tables, available from JMC as RDB3C04)

This report provides thermodynamic property data for R-404A, a zeotropic blend of R-125, R-143a, and R-134a - R-125/143a/134a (44/52/4) - in inch-pound (IP) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling

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point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, specific volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -101 to 66 °C (-150 to 150 °F). A set of tables presents specific volume, enthalpy, and entropy data for superheated vapor at constant pressure for 7-3450 kPa (1-500 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-404A Is Suva(R) HP62.

Thermodynamic Properties of Suva(R) HP62 Refrigerant, technical information report T-HP62-SI (H-49745), DuPont Chemicals, Wilmington, DE, June 1993 (20 pages with 1 figure and 2 tables, RDB3733)

This report provides thermodynamic property data for R-404A, a zeotropic blend of R-125, R-143a, and R-134a - R-125/143a/134a (44/52/4) - in metric (SI) units of measure. It provides physical properties including the chemical formula, molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, specific volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -100 to 65 °C (-148 to 149 °F). A set of tables presents specific volume, enthalpy, and entropy data for superheated vapor at constant pressure for 10-3600 kPa (1-522 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-404A is Suva(R) HP62.

R-406A

R. Döring (Fachhochschule Münster, Germany), **Thermodynamic Characteristics of R-406A - Results of Experimental and Theoretical Tests,** Solvay Specialty Chemicals, Incorporated, Greenwich, CT, undated circa 1994 (68 pages with 2 figures and 59 tables, in English with several labels in German, available from JMC as RDB5127)

This report provides detailed thermodynamic property data for R-406A, a zeotropic blend of R-22, R-600a (isobutane), and R-142b - R-22/600a/142b (55/4/41). It presents a tabular comparison of calculated performance of R-12 and R-406A in a simple process cycle, noting almost the same capacity, piping sizes, and power use, but a higher compression ratio and discharge temperature. The report briefly outlines the methods used to measure properties and calculate derived vapor pressures, liquid densities, and ideal gas specific heat capacities. Tables present physical data for the components, the blend, and R-12 for comparison, in metric (SI) and inch-pound (IP) units of measure. They include the normal bubble and dew point temperatures as well as critical parameters (pressure, temperature, density, and specific volume). The report presents a Martin-Hou equation of state (EOS) and a table showing deviations from measured data. It also provides enthalpy and entropy equations for the superheated region and coefficients to calculate the specific enthalpy, entropy, and exergy. The report concludes with a pressure-enthalpy (Mollier) diagram and detailed tabular data for saturated and superheated conditions in metric (SI) units. The former covers -40 to 100 °C (-40 to 212 °F) and the latter pressures from 20 to 3400 kPa (3-493 psia). Solvay's product name for R-406A is Solkane(R) 406A. [translated from RDB5219]

R. Döring (Fachhochschule Münster, Germany), **Thermodynamische Eigenschaften von GHG 12 -- Ergebnisse experimenteller und theoretischer Untersuchungen** [Thermodynamic Properties of GHG 12 - Results of Experimental and Theoretical Investigations], Solvay Fluor und Derivate GmbH, Hannover, Germany, undated circa 1994 (68 pages with 2 figures and 59 tables, in German, available from JMC as RDB5219)

This report provides detailed thermodynamic property data for R-406A, a zeotropic blend of R-22, R-600a (isobutane), and R-142b - R-22/600a/142b (55/4/41). It presents a tabular comparison of calculated performance of R-12 and R-406A in a simple process cycle, noting almost the same capacity, piping sizes, and power use, but a higher compression ratio and discharge temperature. The report briefly outlines the methods used to measure properties and calculate derived vapor pressures, liquid densities, and ideal gas specific heat capacities. Tables present physical data for the components, the blend, and R-12 for comparison, in metric (SI) and inch-pound (IP) units of measure. They include the normal bubble and dew point temperatures as well as critical parameters (pressure, temperature, density, and specific volume). The report presents a Martin-Hou equation of state (EOS) and a table showing deviations from measured data. It also provides enthalpy and entropy equations for the superheated region and coefficients to calculate the specific enthalpy, entropy, and exergy. The report concludes with a pressure-enthalpy (Mollier) diagram and detailed tabular data for saturated and superheated conditions in metric (SI) units. The former covers -40 to 100 °C (-40 to 212 °F) and the latter pressures from 20 to 3400 kPa (3-493 psia). Solvay's product name for R-406A is Solkane(R) 406A.

R-406A Vapor Table and Mollier-Diagram, Solvay Performance Chemicals, Greenwich, CT, undated circa 1994 (4 pages with 1 figure and 1 table, available from JMC as RDB5128)

This information packet describes and provides data for R-406A, a zeotropic blend of R-22, R-600a (isobutane), and R-142b - R-22/600a/142b (55/4/41). R-406A is identified as an alternative for R-12 for small, hermetic, refrigerating systems such as domestic refrigerators, drink dispensers, and other fixed refrigerating or chilling equipment. The packet includes a table of saturated liquid and vapor data in metric (SI) units of measure for -40 to 100 °C (-40 to 212 °F). It Includes liquid (bubble point) and vapor (dew point) pressures as well as liquid and vapor specific volume, density, enthalpy, and entropy. It concludes with a pressure-enthalpy (Mollier) diagram. Solvay's product name for R-406A is Solkane(R) 406A.

R-407 Series

M. Fukushima, T. Miki, S. Kumano, and S. Ohotoshi (Asahi Glass Company, Limited, Japan), **Thermodynamic Properties of HFC-32, HFC-125, and HFC-134a Mixture**, *Proceedings of the 15th Japan Symposium on Thermophysical Properties*, Japan, 21-24, 1994 (4 pages, rdb8245)

thermodynamic properties of R-407 series blends; thermophysical data

R-407A

J. J. Hurly, J. W. Schmidt, and K. A. Gillis (National Institute of Standards and Technology, NIST), **Equation of State and Ideal-Gas Heat Capacity of a Gaseous Mixture of 1,1,1,2-Tetrafluoroethane, Pentafluoroethane, and Difluoromethane,** *International Journal of Thermophysics*, 18(3):655-681, May 1997 (37 pages with 5 figures and 5 tables, RDB8901)

thermodynamic properties of R-407A identified in the paper as the ternary blend R-32/125/134a (35/30/35 molar); gas-phase equation of state (EOS) and ideal-gas heat capacity for 40-180 °C (104-356 °F) and 50-7,700 kPa (7-1,117 psia); measurements of the gas density with a Burnett apparatus and speed of sound by a cylindrical resonance apparatus; thermophysical data

Klea(R) 60 Data Sheet, bulletin 620250550, ICI Klea, Wilmington, DE, January 1994; republished as **Klea(R) 407A (Klea 60) Data Sheet**, December 1994 (8 pages with 5 tables, available from JMC as RDB4130)

This bulletin provides summary property data and equations to calculate thermophysical properties for R-407A, a zeotropic blend containing R-32, R-125, and R-134a - specifically R32/125/134a (20/40/40) - in inch-pound (IP) units of measure. This formulation was selected to replace R-502 in new refrigeration equipment and also for retrofit in many existing systems. The bulletin tabulates physical properties including the atmospheric bubble and dew points, estimated critical temperature, Trouton's constant, and coefficient of thermal expansion. It also indicates the bubble point pressure and latent heat of vaporization at 21 °C (70 °F) and the saturated vapor density at 1 atmosphere (14.7 psia). The bulletin then presents a Martin-Hou equation of state and formulae to calculate the bubble, mid, and dew point temperatures for the saturation envelope. It also provides formulae for the latent heat of vaporization, ideal gas heat capacity, saturated liquid enthalpy, speed of sound, and liquid and vapor density, viscosity, and thermal conductivity. The document concludes with four tables giving calculated values for these properties at representative pressures of 70-2760 kPa (10-400 psia) and temperatures of -51 to 49 °C (-60 to 120 °F). ICI's product name for R-407A is Klea(R) 60.

Klea 60 Physical Property Data Sheet, SI Units, bulletin CP/33529/1Ed/33/0194, ICI Klea, Runcorn, Cheshire, UK, January 1994 (8 pages with 5 tables, available from JMC as RDB4564)

This bulletin provides summary property data and equations to calculate thermophysical properties for R-407A, a zeotropic blend containing R-32, R-125, and R-134a - specifically R-32/125/134a (20/40/40) - in metric (SI) units of measure. The bulletin tabulates physical properties including the atmospheric bubble and dew point temperatures, estimated critical temperature, Trouton's constant, and coefficient of thermal expansion. It also indicates the bubble point pressure and latent heat of vaporization at 25 °C (77 °F) and the saturated vapor density at 1 atmosphere (14.7 psia). The bulletin then pre-

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sents a Martin-Hou equation of state and formulae to calculate the bubble, mid, and dew point temperatures for the saturation envelope. It also provides formulae for the latent heat of vaporization, ideal gas heat capacity, saturated liquid enthalpy, speed of sound, and liquid and vapor density, viscosity, and thermal conductivity. The document concludes with four tables giving calculated values for these properties at representative pressures of 100-3000 kPa (15-435 psia) and temperatures of -50 to 50 °C (-58 to 122 °F). ICI's product name for R-407A is Klea(R) 60.

Thermodynamic Properties of Klea® 407A (Klea® 60), British Units, bulletin 620250371, ICI Klea, Wilmington, DE, March 1995 (28 pages with 1 figure and 3 tables, limited copies available from JMC as RDB6B30)

This bulletin provides detailed thermodynamic properties for saturated and superheated R-407A - a zeotropic blend containing R-32, R-125, and R-134a, specifically R-32/125/134a (20/40/40) - in inch-pound (IP) units of measure. It comprises three tables, accompanied by notes on system performance with zeotropic blends and instructions to find the evaporator inlet and outlet temperatures based on expansion valve enthalpy and the evaporator pressure. The first presents saturation properties by pressure in 6.9-69 kPa (1-10 psi) increments for 70-3000 kPa (10-430 psia). The tabular data include the dew and bubble points as well as the liquid and vapor density, enthalpy, and entropy. The second table provides density, enthalpy, and entropy data for superheated vapor at constant pressure. The data span the range of 70-2960 kPa (10-430 psia) to temperatures as high as 213 °C (415 °F). The last table presents evaporator inlet temperatures as functions of pressure and enthalpy for 70-690 kPa (10-100 psia). ICI's product name for R-407A is Klea(R) 407A (formerly Klea(R) 60).

Thermodynamic Property Data for Klea 407A, SI Units, bulletin CP/33342/33524/1Ed/R1/43/594, ICI Klea, Runcorn, Cheshire, UK, May 1994 (32 pages with 1 figure and 3 tables, RDB6B31)

This bulletin provides detailed thermodynamic properties for saturated and superheated R-407A - a zeotropic blend containing R-32, R-125, and R-134a, specifically R-32/125/134a (20/40/40) - in metric (SI) units of measure. It comprises three tables, accompanied by notes on system performance with zeotropic blends and instructions to find the evaporator inlet and outlet temperatures based on expansion valve enthalpy and the evaporator pressure. The first presents saturation properties by pressure in 0.1 bar (10 kPa, 1.5 psi increments) for 70-3000 kPa (10-435 psia). The tabular data include the dew and bubble points as well as the liquid and vapor density, enthalpy, and entropy. The second table provides density, enthalpy, and entropy data for superheated vapor at constant pressure. The data span the range of 100-3000 kPa (15-430 psia) to temperatures as high as 168 °C (334 °F). The last table presents evaporator inlet temperatures as functions of pressure and enthalpy for 100-560 kPa (15-80 psia). ICI's product name for R-407A is Klea(R) 407A (formerly Klea(R) 60).

R-407B

Klea(R) 61 Data Sheet, bulletin 620250580, ICI Klea, Wilmington, DE, January 1994; republished as **Klea(R) 4078 (Klea 61) Data Sheet,** December 1994 (8 pages with 1 table, available from JMC as RDB4132)

This bulletin provides summary property data and equations to calculate thermophysical properties for R-407B, a zeotropic blend containing R-32, R-125, and R-134a - specifically R32/125/134a (10/70/20) - in inch-pound (IP) units of measure. This formulation was selected to replace R-502 In existing, low-temperature refrigeration equipment for which R-407A is unsuitable. The bulletin tabulates physical properties including the atmospheric bubble and dew points, estimated critical temperature, Trouton's constant, and coefficient of thermal expansion. It also indicates the bubble point pressure and latent heat of vaporization at 21 °C (70 °F) and the saturated vapor density at 1 atmosphere (14.7 psia). The bulletin then presents a Martin-Hou equation of state and formulae to calculate the bubble, mid, and dew point temperatures for the saturation envelope. It also provides formulae for the latent heat of vaporization, ideal gas heat capacity, saturated liquid enthalpy, speed of sound, and liquid and vapor density, viscosity, and thermal conductivity. The document concludes with four tables giving calculated values for these properties at representative pressures of 70-2760 kPa (10-400 psia) and temperatures of -51 to 49 °C (-60 to 120 °F). ICI's product name for R-407B is Klea(R) 61.

Klea 61 Physical Property Data Sheet, bulletin CP/33530/1Ed/33/0194, ICI Klea, Runcorn, Cheshire, UK, January 1994 (8 pages with 5 tables, available from JMC as RDB4565)

This bulletin provides summary property data and equations to calculate thermophysical properties for R-407B, a zeotropic blend containing R-32, R-125, and R-134a - specifically R-

32/125/134a (10/70/20) - in metric (SI) units of measure. The bulletin tabulates physical properties including the atmospheric bubble and dew points, estimated critical temperature, Trouton's constant, and coefficient of thermal expansion. It also indicates the bubble point pressure and latent heat of vaporization at 20 °C (68 °F) and the saturated vapor density at 1 atmosphere (14.7 psia). The bulletin then presents a Martin-Hou equation of state and formulae to calculate the bubble, mid, and dew point temperatures for the saturation envelope. It also provides formulae for the latent heat of vaporization, ideal gas heat capacity, saturated liquid enthalpy, speed of sound, and liquid and vapor density, viscosity, and thermal conductivity. The document concludes with four tables giving calculated values for these properties at representative pressures of 100-3000 kPa (15-435 psia) and temperatures of -50 to 50 °C (-58 to 122 °F). ICI's product name for R-407B is Klea(R) 61.

Thermodynamic Property Data for Klea(R) 407B (Klea(R) 61), British Units, bulletin 620250391, ICI Klea, Wilmington, DE, March 1995 (28 pages with 1 figure and 3 tables, limited copies available from JMC as RDB6B32)

This bulletin provides detailed thermodynamic properties for saturated and superheated R-407B - a zeotropic blend containing R-32, R-125, and R-134a, specifically R-32/125/134a (10/70/20) - in inch-pound (IP) units of measure. It comprises three tables, accompanied by notes on system performance with zeotropic blends and instructions to find the evaporator inlet and outlet temperatures based on expansion valve enthalpy and the evaporator pressure. The first presents saturation properties by pressure in 7-69 kPa (1-10 psi) increments for 70-2960 kPa (10-430 psia). The tabular data include the dew and bubble points as well as the liquid and vapor density, enthalpy, and entropy. The second table provides density, enthalpy, and entropy data for superheated vapor at constant pressure. The data span the range of 100-3000 kPa (15-435 psia) to temperatures as high as 207 °C (405 °F). The last table presents evaporator inlet temperatures as functions of pressure and enthalpy for 70-690 kPa (10-100 psia). ICI's product name for R-407B Is Klea(R) 407B (formerly Klea(R) 61).

Thermodynamic Property Data for Klea 407B, SI Units, bulletin CP/33343/33525/1Ed/R1/43/594, ICI Klea, Runcorn, Cheshire, UK, May 1994 (32 pages with 1 figure and 3 tables, limited copies available from JMC as RDB6B33)

This bulletin provides detailed thermodynamic properties for saturated and superheated R-407B - a zeotropic blend containing R-32, R-125, and R-134a, specifically R-32/125/134a (10/-70/20) - in metric (SI) units of measure. It comprises three tables, accompanied by notes on system performance with zeotropic blends and instructions to find the evaporator inlet and outlet temperatures based on expansion valve enthalpy and the evaporator pressure. The first presents saturation properties by pressure in 0.1-0.5 bar (10-50 kPa, 1.5-7 psi) increments for 100-3000 kPa (10-435 psia). The tabular data include the dew and bubble points as well as the liquid and vapor density, enthalpy, and entropy. The second table provides density, enthalpy, and entropy data for superheated vapor at constant pressure. The data span the range of 100-3000 kPa (15-435 psia) to temperatures as high as 164 °C (327 °F). The last table presents evaporator inlet temperatures as functions of pressure and enthalpy for 100-560 kPa (15-80 psia). ICI's product name for R-407B is Klea(R) 407B (formerly Klea(R) 61).

R-407C

Genetron(R) 407C Product Brochure, bulletin G525-013, AlliedSignal Incorporated, Morristown, NJ, May 1995 (16 pages with 1 figure and 7 tables, RDB5A31)

This bulletin supplies information on R-407C, a zeotropic blend of R-32, R-125, and R-134a - R-32/125/134a (23/25/52). It was designed to replace R-22 in existing and new equipment including unitary air-conditioners, chillers without flooded evaporators, and commercial refrigeration. The document outlines potential applications and provides physical property information. The data include the chemical name and formula, appearance, molecular weight, normal bubble and dew point temperatures, corresponding heat of vaporization and vapor density, critical parameters (temperature, pressure, specific volume, and density), and flammability. The data also include the bubble and dew point pressure, liquid density, and the vapor and liquid heat capacity, thermal conductivity, and viscosity at 25 °C (77 °F). The bulletin then presents product specifications, provides a pressure-temperature table, and reviews - servicing considerations. It describes tests and indicates that R-407C is stable with metals (aluminum, copper, and steel). The text refers inquiries on desiccants to drier manufacturers. It lists suitability indications for 27 elastomers and plastics. The bulletin suggests use of polyolester lubricants, but indicates that compressor and lubricant manufacturers should be contacted for specific recommendations. It then reviews

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safety information, addressing general toxicity, inhalation effects, skin and eye contact, responses to leaks, flammability, combustibility, and thermal stability. The bulletin offers guidance for storage, handling, leak detection, retrofit, recycling, reclamation, and disposal. It also provides tabular thermodynamic properties (bubble and dew point pressures, liquid density, vapor volume, liquid and vapor enthalpy and entropy, and latent heat of vaporization) for -30 to 70 °C (-60 to 160 °F). The data are provided in both inch-pound (IP) and metric (SI) units. AlliedSignal's product name for R-407C is Genetron(R) 407C.

Klea(R) 407C (Klea 66) Data Sheet, bulletin 620250610, ICI Klea, Wilmington, DE, December 1994 (8 pages with 1 table, limited copies available from JMC as RDB6B34)

This bulletin provides summary property data and equations to calculate thermophysical properties for R-407C, a zeotropic blend containing R-32, R-125, and R-134a - specifically R-32/125/134a (23/25/52) - in inch-pound (IP) units of measure. This formulation was selected to replace R-22 in new low temperature refrigeration equipment and also for retrofit in many existing systems. The bulletin tabulates physical properties including the atmospheric bubble and dew points, estimated critical temperature, Trouton's constant, and coefficient of thermal expansion. It also indicates the bubble point pressure and latent heat of vaporization at 21 °C (70 °F) and the saturated vapor density at 1 atmosphere (14.7 psia). The bulletin then presents a Martin-Hou equation of state and formulae to calculate the bubble, mid, and dew point temperatures for the saturation envelope. It also provides formulae for the latent heat of vaporization, ideal gas heat capacity, saturated liquid enthalpy, speed of sound, and liquid and vapor density, viscosity, and thermal conductivity. The document concludes with four tables giving calculated values for these properties at representative pressures of 70-2760 kPa (10-400 psia) and temperatures of -51 to 49 °C (-60 to 120 °F). ICI's product name for R-407C is Klea(R) 407C (formerly Klea(R) 66).

Thermodynamic Properties of Klea(R) 407C (Klea(R) 66), British Units, bulletin 620250411, ICI Klea, Wilmington, DE, January 1994 (28 pages with 1 figure and 3 tables, limited copies available from JMC as RDB6B36)

This bulletin provides detailed thermodynamic properties for saturated and superheated conditions for R-407C, a zeotropic blend containing R-32, R-125, and R-134a - specifically R-32/-125/134a (23/25/52) - in inch-pound (IP) units of measure. It comprises three tables, accompanied by notes on system performance with zeotropic blends and instructions to find the evaporator inlet and outlet temperatures based on expansion valve enthalpy and the evaporator pressure. The first presents saturation properties by pressure in 7-69 kPa (1-10 psi) increments for 70-2960 kPa (10-430 psia). The tabular data include the dew and bubble points as well as the liquid and vapor density, enthalpy, and entropy. The second table provides density, enthalpy, and entropy data for superheated vapor at constant pressure. The data span the range of 70-2960 kPa (10-430 psia) to temperatures as high as 216 °C (420 °F). The last table presents evaporator inlet temperatures as functions of pressure and enthalpy for 70-690 kPa (10-100 psia). ICI's product name for R-407C Is Klea(R) 407C (formerly Klea(R) 66).

Thermodynamic Properties of Suva(R) AC9000 Refrigerant, technical information report T-AC-9000-ENG (H-56606), DuPont Fluoroproducts, Wilmington, DE, April 1994 (24 pages with 1 figure and 2 tables, available from JMC as RDB4764)

This report provides thermodynamic property data for R-407C, a zeotropic blend of R-125, R-143a, and R-134a - R-125/143a/134a (23/25/52) - in inch-pound (IP) units of measure. It provides physical properties including the chemical formula, molecular weight, normal boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, specific volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -101 to 79 °C (-150 to 175 °F). A set of tables presents specific volume, enthalpy, and entropy data for superheated vapor at constant pressure for 7-3800 kPa (1-550 psia). The report concludes with a pressure enthalpy diagram. DuPont's product name for R-407C Is Suva(R) AC9000.

Thermodynamic Properties of Suva(R) AC9000 Refrigerant, technical information report T-AC-9000-SI (H-56607), DuPont Fluoroproducts, Wilmington, DE, April 1994 (20 pages with 1 figure and 2 tables, available from JMC as RDB4765)

This report provides thermodynamic property data for R-407C, a zeotropic blend of R-125, R-143a, and R-134a - R-125/143a/134a (23/25/52) - in metric (SI) units of measure. It provides physical properties including the chemical formula, molecular weight, normal boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Peng-Robinson-Stryjek-Vera (PRSV) equation of state and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate vapor pressure and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, specific volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -100 to 79 °C (-148 to 174 °F). A set of tables presents specific volume, enthalpy, and entropy data for superheated vapor at constant pressure for 10-4000 kPa (1.5-580 psia). The report concludes with a pressure-enthalpy diagram. DuPont's product name for R-407C is Suva(R) AC9000.

Transport Properties of Suva 9000 Refrigerant, product information report ART-26 (H-60081), DuPont Chemicals, Wilmington, DE, November 1994 (28 pages with 22 figures, available from JMC as RDB5129)

This report provides plots and equations for estimation of transport properties for R-407C, a zeotropic blend of R-125, R-143a, and R-134a -R-125/143a/134a (23/25/52) - as functions of temperature. Saturated liquid viscosity, kinematic viscosity, thermal conductivity, and Prandtl number; vapor viscosity and thermal conductivity at atmospheric and high (100-3,000 kPa, 15-450 psia) pressures; vapor heat capacity; and vapor heat capacity ratio (C_p/C_v) are addressed. The plots and equations are repeated in inch-pound (IP) and metric (SI) units. The equations are based on curve fits of measured data. DuPont's product name for R-407C is Suva(R) 9000.

Thermodynamic Property Data for **Klea**(R) **Klea**(R) **66, SI Units,** bulletin CP/34434/34214/2Ed/43/3941, ICI Klea, Runcorn, Cheshire, UK, March 1994 (32 pages with 1 figure and 3 tables, limited copies available from JMC as RDB6B37)

This bulletin provides detailed thermodynamic properties for saturated and superheated conditions for R-407C, a zeotropic blend containing R-32, R-125, and R-134a - specifically R-32/-125/134a (23/25/52) - in inch-pound (IP) [contrary to the title] units of measure. It comprises three tables, accompanied by notes on system performance with zeotropic blends and instructions to find the evaporator inlet and outlet temperatures based on expansion valve enthalpy and the evaporator pressure. The first presents saturation properties by pressure in 7-69 kPa (1-10 psi) increments for 70-2960 kPa (10-430 psia). The tabular data include the dew and bubble points as well as the liquid and vapor density, enthalpy, and entropy. The second table provides density, enthalpy, and entropy data for superheated vapor at constant pressure. The data span the range of 70-2960 kPa (10-430 psia) to temperatures as high as 216 °C (420 °F). The last table presents evaporator inlet temperatures as functions of pressure and enthalpy for 70-690 kPa (10-100 psia). ICI's product name for R-407C is Klea(R) 407C (formerly Klea(R) 66).

R-408A

Forane(R) FX-10, technical digest, Elf Atochem North America, Incorporated, Philadelphia, PA, undated circa 1994 (4 pages with 4 tables, available from JMC as RDB4770)

This bulletin supplies information on R-408A, a near-azeotropic blend of R-125, R-143a, and R-22 - R-125/143a/22 (7/46/47). R-408A was formulated as a retrofit refrigerant in low and medium temperature refrigeration systems designed for R-502. The bulletin notes that R-404A is recommended to replace R-502 in new equipment. A table compares physical and environmental property data for R-408A and R-502 in inch-pound (IP) units. The table lists the chemical formulation, average molecular weight, normal boiling point, heat of vaporization, vapor and liquid density at the boiling point and 25 °C (77 °F), critical parameters (temperature and pressure), specific heat of the liquid at the same temperature and of the vapor at atmospheric pressure, maximum temperature glide, ozone depletion potential (ODP), and halocarbon global warming potential (HGWP). The table also shows R-408A to be nonflammable at test temperatures up to 100 °C (212 °F). A second table gives the saturated vapor pressures of R-408A and R-502 for -43 to 60 °C (-45 to 140 °F). A third presents the saturated liquid and vapor pressures, densities, and enthalpies for the same range. The document briefly discusses considerations for use of near-azeotropic blends with attention to temperature glide, composition changes, and charging implications. It also reviews performance, lubrication, and materials compatibility considerations for retrofit systems. It notes that R-408A can be used with mineral oil, alkylbenzene, or polyolester lubricants. It also outlines a nine-step retrofit procedure to convert equipment from R-502 to R-408A. The digest concludes with container identification for R-408A and other alternative refrigerants. Elf Atochem's product name for R-408A Is Forane(R) FX-10.

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R-409A

Forane[R] FX-56, technical digest, Elf Atochem North America, Incorporated, Philadelphia, PA, undated circa 1994 (4 pages with 2 figures and 4 tables, available from JMC as RDB4771)

This bulletin supplies information on R-409A, a zeotropic blend of R-22, R-124, and R-142b - R-22/124/142b (60/25/15). R-409A was formulated as a retrofit refrigerant for R-12 in low and medium temperature refrigeration systems where removal of mineral oil is difficult. A table summarizes physical and environmental property data for R-409A in inch-pound (IP) units. The table lists the chemical formulation, average molecular weight, normal boiling (bubble) point, heat of vaporization, critical parameters (temperature and pressure), vapor and liquid density at the boiling point and 27 °C (80 °F) respectively, specific heat of the liquid at the same temperature and of the vapor at atmospheric pressure, maximum temperature glide, ozone depletion potential (ODP), and halocarbon global warming potential (HGWP). The table also shows R-409A to be nonflammable. A second table gives the bubble and dew point pressures of R-409A and saturated vapor pressures of R-12 for -34 to 60 °C (-30 to 140 °F). The document briefly discusses retrofit, lubrication, charging procedures, and performance. It notes that R-409A can be used with mineral oil, alkylbenzene, or polyolester lubricants. It also notes that while evaporator pressures will be similar to those with R-12, condenser pressures will be 69-138 kPa (10-20 psi) higher. The bulletin then explains terminology associated with zeotropic blends, including *bubble point, dew point, fractionation*, and *glide*. It then reviews the typical behavior of R-409A in an evaporator, explaining how the composition changes during boiling. The bulletin outlines an eight-step retrofit procedure to convert equipment from R-12 to R-409A and provides guidance on setting system temperatures with the blend. The digest concludes with container identification for R-409A and other alternative refrigerants. Elf Atochem's product name for R-409A Is Forane[R] FX-56.

R-410 Series

Y. Chernyak (University of Delaware, USA), P. V. Zhelezny (Odessa State Academy of Refrigeration, Ukraine), and M. E. Paulaitis (University of Delaware, USA), **Thermodynamic Properties of HFC-32/HFC-125 Mixtures and an Estimation of Its Environmental Impact and Utility in Refrigeration**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 429-434, July 1996 (6 pages with 5 figures and 2 tables, RDB6C19)

equation of state (EOS) for R-32/125 (R-410 series) blends; performance and total equivalent warming impact (TEWI) comparisons for R-32/-125 (20/80), (40/60), (60/40), and (80/20) with R-22, R-290, R-502, and R-717

H-L. Zhang, **Thermodynamic Property Representation for the R-32/125 Binary System by a New Cubic Equation of State,** *Fuel and Energy Abstracts*, 39(3):215, May 1998 (1 page, rdb8C27)

equation of state (EOS) for R-32/125 (R-410 series) blends; thermodynamic properties, thermophysical data

R-410A

Genetron[R] AZ-20 (R-410A) Product Brochure, bulletin G525-012, AlliedSignal Incorporated, Morristown, NJ, October 1996 (16 pages with 4 figures and 7 tables, limited copies available from JMC as RDB7211)

This bulletin supplies information on R-410A, a patented blend of R-32 and R-125 - R-32/125 (50/50) - that behaves like an azeotrope. It was designed to replace R-22 in a variety of new equipment including unitary air-conditioners, chillers, and commercial refrigeration. The document outlines potential applications and provides physical property data including the chemical name and formula, appearance, molecular weight, normal boiling point, corresponding heat of vaporization and vapor density, critical parameters (temperature, pressure, specific volume, and density), and flammability. It also indicates the liquid density, vapor pressure, and the vapor and liquid heat capacity, thermal conductivity, and viscosity at 25 °C (77 °F). The bulletin then presents product specifications and provides both a pressure-temperature table and pressure-enthalpy (Mollier) diagrams. It reviews servicing considerations presents a tabular summary of the stability of R-410A with polyolester lubricants (Mobil EAL 22 and 32, Castrol SW 32) and metals (aluminum, copper, and steel). The text refers inquiries on desiccants to drier manufacturers, but provides a solubility plot for water in R-410A and lists suitability indications for 27 elastomers and plastics. The bulletin suggests use of polyolester lubricants, but indicates that compressor and lubricant manufacturers should be contacted for specific recommendations. It then reviews safety information, addressing general toxicity, inhalation effects, skin and eye contact, responses to leaks, flammability, combustibility, and thermal stability. The bulletin offers guidance for storage, handling, leak detection, retrofit, recycling, reclamation, and disposal. It also provides tabular thermodynamic properties (pressure, liquid density, vapor volume, liquid and vapor enthalpy and entropy, and latent heat of vaporization) for -30 to 70 °C (-60 to 160 °F) [tables cover dissimilar ranges for the two sets of units]. Formulae are presented to calculate thermodynamic properties, including vapor pressure, liquid density, and ideal gas heat capacity correlations. A Martin-Hou equation of state also is presented. The data are provided in both inch-pound (IP) and metric (SI) units. AlliedSignal's product name for R-410A is Genetron(R) AZ-20.

R-410B

D. B. Bivens, A. Yokozeki (DuPont Chemicals), and V. Z. Geller (Thermophysics Research Center), **Thermodynamic Properties of R32/R125 Mixture**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 107-116, October 1995 (10 pages with 1 figure and 7 tables, available from JMC as RDB5A51)

R-410B, critical parameters, vapor pressure, saturated liquid and vapor densities, PVT measurements, Martin Hou equation of state (EOS)

D. B. Bivens, A. Yokozeki (DuPont Chemicals), and V. Z. Geller (University of Delaware), **Thermodynamic Properties of R32/R125 Mixture**, *Proceedings of the Fourth Asian Thermophysical Properties Conference* (Tokyo, Japan, 5-8 September 1995), 2:327-330, 1995 (4 pages, rdb5265)

thermodynamic properties of R-410B; thermophysical data

Other Zeotropes

R. S. Agarwal, M. Ramaswamy, and V. K. Srivastava, **Transport Properties of Ternary Near-Azeotropic Mixtures**, research paper, Indian Institute of Technology (IIT), New Delhi, India, October 1993; republished in *International Journal of Refrigeration* (IJR), 18(2):132-138, February 1995 (18/7 pages with 6 figures and 11 tables, research paper available from JMC as RDB3A70)

This paper presents transport properties for four ternary zeotropic formulations of R-22/152a/124, namely 53/13/34 (R-401A), 61/11/28 (R-401B), 33/15/32 (R-401C), and 36/24/40. The properties were calculated, using estimation techniques documented in the paper. Correlations and plots summarizing the findings are presented, the latter for -53 to 97 °C (-63 to 207 °F). The paper addresses liquid and vapor thermal conductivity, specific heat, and viscosity. The estimation techniques used were evaluated by computing the properties of R-500 and comparing the results with published data. Potential applications of the four near-azeotropic blends are discussed briefly.

Y. Chernyak (Odessa State Academy of Refrigeration, Ukraine), **Thermodynamic Properties of Mixtures of Ozone-Safe Refrigerants FC218-HFC134a and HFC152a-HFC134a**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:123-130, 1995 (8 pages with 6 figures, rdb7732)

measurements of PVT and critical point parameters for R-218/134a and R-134a/152a using a variable volume apparatus with an optical cell: results are fitted to a cubic equation of state and a Kesselman-type equation; correlations for the coexisting densities and pressure along the saturation boundary; new methods for calculating the saturated vapor density; estimates of the thermodynamic efficiencies of the azeotrope R-218/134a (40.5/59.5) and quasi-azeotrope (a blend with uniform composition of the liquid and vapor phases coexisting in equilibrium within the entire concentration interval) R-134a/152a in vapor-compression cycles; R-134a/152a (20/80) is a close match for R-12 and indicated to be nonflammable

D. R. Defibaugh and G. Morrison (National Institute of Standards and Technology, NIST), **Compressed Liquid Densities, Saturated Liquid Densities, and Saturation Pressures of Mixtures: Difluoromethane + 1,1,1,2-Tetrafluoroethane, Difluoromethane + 1,1-Difluoroethane**, *Proceedings of the 1992 International Refrigeration Conference - Energy Efficiency and New Refrigerants,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 2:473-478, July 1992 (6 pages with 8 figures, RDB2830)

thermodynamic properties of R-32/134a and R-32/152 blends: thermophysical data

K. Fujiwara, A. Sato, and S. Ide (Daikin Industries, Limited, Japan), **Vapor-Liquid Equilibria of HFC-23/32/134a Mixtures**, paper A101, *Proceedings of the 15th Japan Symposium on Thermophysical*

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Properties, Japan, 1-4, 1994 (4 pages with 4 figures and 4 tables; in Japanese with abstract, equations, figures, and tables in English; RDB5A06)

This paper presents isothermal, vapor-liquid equilibrium data for the binary zeotropes of R-23/32, R-23/134a, and R-32/134a. Both tabular data and pressure-composition plots are provided. The apparatus used for the measurements is described and shown schematically. The critical parameters (temperature and pressure) and acentric factors are tabulated for R-23, R-32, and R-134a. Interaction parameters and averaged comparisons to measured data are then compared to measured data for both the Soave-Redlich-Kwong (SRK) and Peng-Robinson (PR) equations of state (EOS), for the three binary pairs. Deviations to the bubble and dew point pressures and densities are tabulated for three ternary blends of R-23/32/134a, namely (1.0/29.7/69.3), (2.0/28.0/70.0), and (5.0/28.5-/66.5). The paper concludes that the two equations predict the saturated pressure and vapor density with almost the same accuracy, but that the PR equation of state is more accurate for the liquid density.

K. Fujiwara, H. Momota, and M. Noguchi (Daikin Industries, Limited, Japan), **Vapor-Liquid Equilibria of HFC-32 Mixtures**, *Proceedings of the 13th Japan Symposium on Thermophysical Properties*, Akita, Japan, 61-64, 1992 (4 pages, rdb4875)

thermodynamic properties of R-32 blends: thermophysical data

J. S. Gallagher, **Thermodynamic Properties of a Geothermal Working Fluid: 90% Isobutane - 10% Isopentane**, NBS Technical Note 1234, National Institute of Standards and Technology (NIST, then the National Bureau of Standards, NBS), Gaithersburg, MD, 1987 (available from GPO, rdb-4C08)

thermodynamic properties of R-600a, R-601a, and R-600a/601a (90/10); thermophysical data

V. Z. Geller, **Thermophysical Properties of Multicomponent Refrigerants**, *Inzhenerno-Fizicheskii Zhurnal* [Journal of Engineering Physics], Minsk, Belarus (then USSR), 55(4):620-624, 1988 (5 pages probably in Russian, rdb5486)

thermophysical data

Y. Higashi (Iwaki Meisel University, Japan), **Vapor-Liquid Equilibrium, Coexistence Curve, and Critical Locus for Binary HFC-32/HFC-134a Mixtures**, *International Journal of Thermophysics,* 16(5):1175-1184, September 1995 (10 pages, rdb-8917)

thermodynamic property measurements of R-32/134a blends: presents vapor-liquid equilibria (VLE) were measured by a static method in the temperature range of 10-40 °C (50-104 °F); discusses the temperature dependence of the binary interaction parameter for the Soave-Redlich-Kwong (SRK) and Carnahan-Starling-De-Santis (CSD) equations of state (EOS); summarizes measurements of the vapor-liquid coexistence curve near the critical point by observation of meniscus disappearance; indicates the critical temperatures and densities of R-32/134a (30/70) and (70/30) on the basis of the saturation densities along the coexistence curve in the critical region; presents a correlation of the critical locus as a function of composition for this blend

H. Hipkin, **Experimental Vapor-Liquid Equilibrium Data for Propane-Isobutane**, *AIChE Journal,* 12(3):484-487, 1966 (4 pages, rdb5711)

thermodynamic properties of R-290, R-600a, and R-290/600a blends; thermophysical data

T. Hozumi, H. Sato, and K. Watanabe (Keio University, Japan), **Second Virial-Coefficients of R-32/-134a Based on the Sound-Velocity Measurements**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:321-328, 1995 (8 pages with 4 figures and 1 table, rdb7821)

experimental determination of sound velocities of gaseous R-32, R-134a, and R-32/134a blends using a spherical resonator; correlation for the second virial coefficients of R-32/134a covering the entire range of compositions; thermodynamic properties; thermophysical data

Y. Ikeya (Sumitomo Heavy Industries, Limited, Japan), C-C. Piao, S. Yokota, H. Sato, and K. Watanabe (Keio University, Japan), **Measurements of Gaseous Isobaric Specific Heat Capacity of Alternative Refrigerants**, *Preprints of the 11th Symposium on Thermophysical Properties* (Boulder, CO, 23-27 June 1991), American Society of Mechanical Engineers (ASME), New York, NY, 1991; republished in *Fluid Phase Equilibria*, 80(4):119-129, 30 November 1992 (11 pages, rdb5474)

describes a new apparatus that applies gas-flow calorimetry to measure the isobaric specific heat of superheated vapors with high accuracy at temperatures up to 200 °C (392 °F) and pressures up to 10 MPa (1450 psia): estimates the experimental uncertainties in temperature, pressure, and isobaric specific heat as not greater than ±0.005 °C (0.009 °F), ±4 kPa (0.6 psia), and ±0.26%, respectively; presents four isobaric specific heat values of R-22 vapor and compares them with data published by others; presents four isobaric specific heat values of R-134a vapor and compares them to ideal-gas specific heat derived from sound velocity measurements, spectroscopic measurements, and existing equations of state (EOSs) for R-134a

L. R. C. Kahre, **Liquid Density of Light Hydrocarbon Mixtures**, *Journal of Chemical and Engineering Data*, 18(3):267-270, 1973 (4 pages, rdb5713)

thermodynamic properties of R-290/600a and others; thermophysical data

S. B. Kiselev (Russian Academy of Sciences, Russia) and J. V. Sengers (University of Maryland), **An Improved Parametric Crossover Model for the Thermodynamic Properties of Fluids in the Critical Region**, *International Journal of Thermophysics*, 14(1):1-32, 1993 (32 pages, rdb9126)

crossover equation of state (EOS) model to represent thermodynamic properties of near the critical point

H. B. Lange and F. P. Stein, **Volumetric Behavior of a Polar-Nonpolar Gas Mixture: Trifluoromethane-Tetrafluoromethane**, *Journal of Chemical and Engineering Data*, 15:56-61, 1970 (6 pages, rdb4B37)

thermodynamic properties of R-14, R-23, and R-14/23 blends: thermophysical data

J. Luettmer-Strathmann and J. V. Sengers (University of Maryland), **The Transport Properties of Fluid Mixtures Near the Vapor-Liquid Critical Line**, *Journal of Chemical Physics*, 104(8):3026-3047, 22 February 1996 (25 pages with 16 figures and 4 tables, RDB6404)

R-170/744 (ethane/carbon dioxide), mode-coupling theory for the dynamics of critical fluctuations to binary fluid mixtures near the vapor-liquid critical line, compares a proposed crossover model with experimental thermal conductivity data in the critical region, provides constants for the crossover model and critical parameters (temperature, pressure, and density) for 25/75, 26/74, 50/50, and 74/26 mixtures of R-170 and R-744 by mole fraction, compares calculated results with experimental data for thermal diffusivity, thermal conductivity, and viscosity

J. Luettmer-Strathmann, J. V. Sengers, and G. A. Olchowy (University of Maryland), **Non-Asymptotic Critical Behavior of the Transport Properties of Fluids**, *Journal of Chemical Physics*, 103(17):7482-7501, 1 November 1995 (20 pages with 15 figures and 3 tables, RDB6405)

R-170/744 (ethane/carbon dioxide), mode-coupling theory for the dynamics of critical fluctuations to fluids near the vapor-liquid critical line, derivation of crossover equations

Y. Maezawa, H. Sato, and K. Watanabe Keio University, Japan), **Some Correlations for Saturated Liquid Density of Refrigerant Mixtures**, *Nippon Reito Kyokai Ronbunshu* [Transactions of the JAR], Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 10(1):125-133, 1993 (9 pages in Japanese, rdb4877)

thermodynamic properties of blends; thermophysical data

G. A. Olchowy and J. V. Sengers (University of Maryland), **Crossover from Singular to Regular Behavior of the Transport Properties of Fluids in the Critical Region**, *Phys. Research Letters*, 61:15-18, 1988 (4 pages, rdb8468)

crossover model to represent thermophysical properties near the critical point

A. Osajima, H. Sato, and K. Watanabe (Keio University, Japan), **Reliable Thermodynamic Property Data of Binary Refrigerant Mixtures of R-32/134a and R-32/125**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 24-26 October 1994), Alliance for Responsible Atmospheric Policy, Arlington, VA, 85-94, October 1994 (8 pages with 11 figures and 6 tables, RDB8244)

thermodynamic properties of R-32/125 (R-410 series blends) and R-32/134a: thermophysical properties

W. R. Parrish, **Compressed Liquid Densities of Propane-Normal Butane Mixtures Between 10 °C and 60 °C at Pressures Up to 9.6 MPa**, *Fluid Phase Equilibria*, 25:65-90, 1986 (26 pages, rdb7A38)

thermodynamic properties of R-290/600 for 10-60 °C (50-140 °F) up to 9.6 MPa (1400 psia); thermophysical data

W. R. Parrish, **Calculation of Compressed Liquid Ethane-Propane Mixture Densities for Custody Transfer at Pressures Up to 14 MPa**, *Fluid Phase Equilibria,* 23:193-211, 1985 (9 pages, rdb7A39)

thermodynamic properties of R-170/290 up to 14 MPa (2000 psia); thermophysical data

C-C. Piao, M. S. Noguchi (Daikin Industries, Limited), H. Sato, and K. Watanabe (Kelo University, Japan), **Thermodynamic Properties of HFC-32/HFC-134a Binary System**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 37-42, July 1994 (6 pages with 5 figures and 2 tables, RDB4807)

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thermodynamic properties of R-32/134a (30/70); thermophysical data

A. A. Povodyrev (University of Maryland, USA, and Russian Academy of Sciences, Russia), G. X. Jin (University of Maryland), S. B. Kiselev (Russian Academy of Sciences, Russia) and J. V. Sengers (University of Maryland), **Crossover Equation of State for the Thermodynamic Properties of Mixtures of Methane and Ethane in the Critical Region**, *International Journal of Thermophysics,* 17(4):909-944, July 1996 (36 pages with 18 figures and 3 tables, RDB7A56)

crossover equation of state (EOS) model to represent the thermodynamic properties of R-50/170 near the critical point; plait point

D. Vollmer (Forschungszentrum für Kälte- and Umwelttechnik GmbH, FKU, Germany) and E. Findeisen (Foron Hausgeräte GmbH, Germany), **Calculation of Thermodynamic and Thermophysical Properties of Binary Mixture Propane/Isobutane**, *New Applications of Natural Working Fluids in Refrigeration and Air Conditioning* (proceedings of the meeting of IIR Commission B2, Hannover, Germany, 10-13 May 1994), International Institute of Refrigeration (IIR), Paris, France, 119-130, 1994 (12 pages with 7 figures and 5 tables, RDB5705)

thermodynamic properties of R-290, R-600a, and R-290/600a blends: Redlich-Kwong-Soave (RKS) and Lee-Kesler-Plöcker (LKP) equations of state (EOS), thermophysical data

J. V. Widiatmo, T. Sato, H. Kiyoura, H. Sato, and K. Watanabe (Keio University, Japan), **Representation of Thermodynamic Properties of Alternative Refrigerant Mixtures HFC-32/134a and HFC-32/125**, *CFCs, the Day After* (proceedings of the IIR meeting, Padova, Italy, 21-23 September 1994), International Institute of Refrigeration (IIR), Paris, France, 453-460, September 1994 (8 pages, RDB-9603)

thermodynamic properties of R-32/134a and R-410 series (R-32/125) blends; thermophysical data

FRIGC(R) FR-12(TM) Refrigerant Specifications, InterCool Energy Corporation, Latham, NY, 1996 (2 pages with 1 figure and 2 tables, RDB6C06)

This product specification sheet provides data on a ternary zeotropic blend of R-124, R-134a, and R-600 - R-134a/124/600 (59/39/2) - in inch-pound (IP) and metric (SI) units of measure. The blend is described as a replacement for R-12 in mobile air-conditioning (MAC) applications. The bulletin indicates that the blend operates in the same pressure range as R-12, even at high ambient temperatures, and is compatible the mineral oil used in MAC compressors. A table summarizes selected physical properties including the normal bubble and dew points, corresponding vapor and liquid densities, latent heat of vaporization, and critical parameters (temperature, pressure, and density). It also includes the vapor pressure, solubility in water, and the liquid and vapor thermal conductivities and heat capacities at 25 °C (77 °F). It concludes with the ozone depletion potential (ODP), global warming potential (GWP), and flammability limits (indicated as none). The product sheet then discusses service considerations including charging and recovery. It briefly reviews compatibility findings with plastics, elastomers, metals, desiccants, and lubricants as well as leak detection. A table and plot compare the vapor pressure for the blend at its bubble and dew points to that for R-12 at -7 to 93 °C (20-200 °F). InterCool Energy Corporation's product name for this blend is FRIGC(R)FR-12(TM)

Meforex(R) DI-36, Ausimont S.p.A., Bollate, Italy, undated circa 1996 (2 pages with 1 figure and 2 tables, RDB7202)

This product bulletin provides data on a ternary zeotropic blend of R-22, R-124, and R-600 - R-22/124/600 (50/47/3) - in metric (SI) units of measure. The blend is described as a replacement for R-12, in refrigeration applications where retrofitting to R-134a is not convenient for economic or technological reasons. The bulletin indicates that the blend closely matches the thermodynamic properties of R-12 for evaporation temperatures exceeding -25 °C (-13 °F), and is compatible the mineral oil over a wide range of temperatures. A table summarizes selected physical properties including the normal bubble and dew point temperatures, critical parameters (temperature, pressure, and density), corresponding vapor density and latent heat of vaporization, and the liquid densities and vapor pressures at -25 °C (-13 °F) and 25 °C (-77 °F). It also includes the liquid and vapor thermal conductivites, solubility in and of water, and flammability limits (none) at the latter temperature. It concludes with a recommended exposure limit for chronic toxicity (900 ppm w/w) and ozone depletion potential (ODP, 0.034). The product sheet then reviews compatibility findings with plastics, elastomers, metals, desiccants, and lubricants as well as storage recommendations and available packaging. A table and plot compare the vapor pressure for the blend, R-12, and R-134a for -40 to 60 °C (-40 to 140 °F). Ausimont's product name for this blend is Meforex(R) DI-36.

Meforex(R) DI-44, Ausimont S.p.A., Bollate, Italy, undated circa 1996 (2 pages with 1 figure and 2 tables, RDB7203)

This product bulletin provides data on a tetrary zeotropic blend of R-22, R-125, R-143a, and R-290 - R-125/143a/290/22 (42/6/2/50) - in metric (SI) units of measure. The blend is described as a near-azeotropic replacement for R-502 in commercial and transport refrigeration. The bulletin indicates that the blend exhibits a vapor pressure-temperature relationship equivalent to that of R-502 and some miscibility with mineral oils. A table summarizes selected physical properties including the normal bubble and dew point temperatures, critical parameters (temperature, pressure, and density), corresponding vapor density and latent heat of vaporization, and the liquid densities and vapor pressures at -25 °C (-13 °F) and 25 °C (-77 °F). It also includes the liquid and vapor thermal conductivities, solubility in and of water, and flammability limits (none) at the latter temperature. It concludes with a recommended exposure limit for chronic toxicity (1,000 ppm w/w) and ozone depletion potential (ODP, 0.02). The product sheet then reviews compatibility findings with plastics, elastomers, metals, desiccants, and lubricants as well as storage recommendations and available packaging. A table and plot compare the vapor pressure for the blend and R-502 for -50 to 60 °C (-58 to 140 °F). Ausimont's product name for this blend is Meforex(R) DI-44.

R-500

T. E. Morsey, **Thermodynamische Eigenschaften von R500** [Thermodynamic Properties of R-500], *Kältetechnik-Klimatisierung,* Germany*,* 20(4):94 ff, 1968 (in German, rdb7A52)

thermodynamic properties of R-500; thermophysical data

J. V. Sinka and K. P. Murphy (AlliedSignal Incorporated, then Allied Chemical Corporation), **Pressure-Volume-Temperature Relations for a Mixture of Difluorodichloromethane and 1,1-Difluoroethane**, *Journal of Chemical and Engineering Data,* 12(3):315-316, 1967 (2 pages, rdb3933)

thermodynamic properties of R-500: equation of state (EOS); PVT; thermophysical data

Freon® 500 - Tables of Thermodynamic Properties, technical bulletin T-500 (E-36103), E. I. duPont de Nemours and Company, Incorporated, Wilmington, DE, undated circa 1988 (16 pages with 2 tables, RDB3C01)

This report provides thermodynamic property data for R-500 in inch-pound (IP) units of measure. It comprises two tables. The first presents pressure as well as liquid and vapor specific volume, density, enthalpy, heat of vaporization, and entropy at saturation conditions for temperatures of -51 to 104 °C (-60 to 220 °F). The second presents specific volume, enthalpy, and entropy for the superheated vapor at temperatures of -46 to 238 °C (-50 to 460 °F) and pressures of 55-2850 kPa (8-414 psia). DuPont Chemical's product name for R-500 is Freon(R) 500.

R-502

J. J. Martin (University of Michigan) and R. C. Downing (E. I. duPont de Nemours and Company), **Thermodynamic Properties of Refrigerant 502**, paper 2150, *Transactions* (Annual Meeting, Kansas City, MO, 28 June - 1 July 1970), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 76(2):129-139, 1970 (11 pages with 14 tables, RDB3934)

thermodynamic properties of R-502: equation of state (EOS), thermophysical data

Thermophysical Properties of Refrigerants (R-502, Azeotrope of R-22 and R-115), *Nippon Reito Kyokai* [Japanese Association of Refrigeration, JAR], Tokyo, Japan, November 1986 (164 pages with 21 figures and 44 tables, in both Japanese and English, rdb0405)

This comprehensive volume summarizes critical, thermodynamic, transport, physical, chemical, compatibility, and other data available on R-502, an azeotrope comprising 48.8% R-22 and 51.2% R-115 by weight. Included are tabular data and/or plots for PVT properties, enthalpy, entropy, isobaric and isochoric specific heat capacity, specific heat ratio, isentropic expansion exponent, speed of sound, surface tension, viscosity, kinematic viscosity, thermal conductivity, thermal diffusivity, Prandtl number, solubility, refractive index, and dielectric constant. An extended Benedict-Webb-Rubin (BWR) equation of state is presented and compared to other equations and data. Relations also are presented for key equilibrium properties. Data are tabulated for the solubility of water in R-502 and of R-502 In alkylbenzene lubricant. Limited data are provided on the stability of R-502 In the presence of metals and oil and on linear swell for neoprene GN, Buna(TM) N, natural rubber, GR-I, GR-S, and polysulfide rubber. Published safety data, including toxicity and flammability, are summarized. The volume contains an extensive list of references as well as discussion of the ranges and differences among property sources identified. An introductory section outlines conversions among several metric sys-

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tems, including SI, and inch-pound units. An appendix addresses compliance with the Japanese Industrial Standards (JIS), noting that the quality of R-502 is not covered; JIS K1528-1982 requirements for the quality of R-22 are summarized.

R-503

J. V. Sinka, E. Rosenthal, and R. P. Dixon (AlliedSignal Incorporated, then Allied Chemical Corporation), **Pressure-Volume-Temperature Relations for a Mixture of Monochlorotrifluoromethane and Trifluoromethane**, *Journal of Chemical and Engineering Data*, 15(1):73-74, 1970 (2 pages, rdb3935)

R-503, thermodynamic properties, equation of state (EOS)

Genetron[(R)] 503 Refrigerant for Cascade Systems, bulletin RTB-503B (22-503B), AlliedSignal Incorporated (then Allied Chemical Corporation), Morristown, NJ, 1976 (16 pages with 7 figures and 2 table, RDB4104)

This bulletin presents physical property, performance, and application data for R-503, an azeotropic blend of R-23 and R-13 - R-23/13 (40.1/59.9). A table identifies the composition and lists key physical data including critical parameters, flammability, toxicity, color, and odor. Two tables provides performance data at saturated cycle conditions of -87 °C (-125 °F) evaporating and -34 °C (-30- °F) condensing for R-503, compared to -82 °C (-115 °F) and -29 °C (-20 °F) for R-13, and for both at -84 °C (-120 °F) evaporating and -34 °C (-30 °F) condensing. The bulletin describes use of R-503 as the low stage of a cascade system as an alternative to R-13, R-23, and R-170. It discusses system design and operation as well as lubricant considerations, citing addition of no more than 5-10% pentane to mineral oils for improved miscibility. It briefly covers water solubility, stability, compatibility, handling, charging, leak testing, and safety precautions. A series of figures in inch-pound units compare the vapor pressure and temperature relations or R-13, R-170, and R-503 as well as the compressor displacement, solubility of water, and thermal conductivity of R-13 and R-503. Two final plots show the vapor heat capacity ratio and sonic velocity of R-503.

Genetron[(R)] 503 Refrigerant, Thermodynamic Properties, AlliedSignal Incorporated (then Allied Chemical Corporation), Morristown, NJ, 1970 (6 pages with 1 figure and 1 table, RDB3A10)

This bulletin presents physical property, performance, and thermodynamic data for R-503, an azeotropic blend of R-23 and R-13 - R-23/13 (40.1 /59.9). A table identifies the composition, lists key physical data including critical parameters, flammability, toxicity, color, and odor. A second table provides performance data at saturated cycle conditions of -84 °C (-120 °F) evaporating and -34 °C (-30 °F) condensing. A final table gives thermodynamic (temperature, pressure, vapor volume, liquid density, enthalpy, and entropy) at saturation conditions for -129 °C (-200 °F) to the critical temperature, 19.5 °C (67.1 °F). A pressure-enthalpy diagram is provided in inch-pound units of measure.

R-507 Series

J. V. Widiatmo, H. Sato, and K. Watanabe (Keio University, Japan), **Bubble-Point Pressures and Liquid Densities of Binary R-125 plus R-143a System,** *International Journal of Thermophysics,* 16(3):801-810, May 1995 (10 pages, rdb8916)

presents bubble-point pressures and saturated-liquid densities for R-125/143a (R-507 series) blends at temperatures from 7-57 °C (44-134 °F): the data were measured with a magnetic densimeter coupled with a variable volume cell employing a metallic bellows; provides Peng-Robinson (PR) equation for the bubble-point pressures and a modified Hankinson-Brobst-Thomson (HBT) equation for the saturated-liquid densities to estimate the thermodynamic behavior of vapor-liquid equilibria (VLE) of this binary mixture; identifies optimized binary interaction parameters

R-507A (R-507)

P. B. Logsdon, E. A. E. Lund, I. R. Shankland, and R. R. Singh (AlliedSignal Incorporated), **Properties of a Zero ODP Azeotropic Refrigerant Blend, HFC-125/HFC-143a**, *Proceedings of the International CFC and Halon Alternatives Conference* (Washington, DC), Alliance for Responsible CFC Policy, Arlington, VA, 47-54, September 1992 (10 pages with 1 figure and 7 tables, RDB2A02)

R-507A; R-125/143a, thermophysical data

Genetron[(R)] AZ-50 Product Brochure, bulletin G-525-030, AlliedSignal Incorporated, Morristown, NJ, January 1997 (16 pages with 4 figures and 8 tables, limited copies available from JMC as RDB7118)

This bulletin supplies information on R-507A, a patented, azeotropic blend of R-125 and R-143a

- R-125/143a (50/50). It was developed to replace R-502 in low- and medium-temperature commercial refrigeration such as display cases, transport refrigeration, and ice machines. The document outlines potential applications. It provides physical property data including the chemical name and formula, appearance, molecular weight, normal boiling point, corresponding heat of vaporization and vapor density, freezing point range, critical parameters (temperature, pressure, specific volume, and density), and flammability. It also indicates the liquid density, vapor pressure, and the vapor and liquid heat capacity, thermal conductivity, and viscosity at 25 °C (77 °F). The bulletin then presents product specifications, performance data, a pressure-temperature table, and pressure-enthalpy (Mollier) diagrams. The bulletin suggests use of polyolester lubricants and provides a generic miscibility diagram, but indicates that compressor and lubricant manufacturers should be contacted for specific recommendations. A table summarizes the stability of R-507A with polyolester lubricants (Mobil EAL 22 and 32, Castrol SW 32), and metals (aluminum, copper, and steel). The document recommends against introduction of chlorinated materials in systems using R-507A with polyolester lubricants. It identifies potential sources and indicates that the lubricants may be incompatible with them. It also counsels against mixing R-502 and R-507A, since R-115 from the former and R-125 from the latter may form an azeotrope, making recycling and reclamation very difficult. The bulletin lists suitability indications for 29 elastomers and plastics, provides a solubility plot for water in R-507A, and offers recommendations on desiccant driers. It then reviews safety information, addressing general toxicity, inhalation effects, skin and eye contact, responses to leaks, flammability, combustibility, and thermal stability. The bulletin offers guidance for storage, handling, leak detection, retrofit, recycling, reclamation, and disposal. It also provides tabular thermodynamic properties (pressure, liquid density, vapor volume, liquid and vapor enthalpy and entropy, and latent heat of vaporization) for -30 to 70 °C (-60 to 158 °F). Formulae are presented to calculate thermodynamic properties, including vapor pressure, liquid density, and ideal gas heat capacity correlations. A Martin-Hou equation of state also is presented. The data are provided in both inch-pound (IP) and metric (SI) units. AlliedSignal's product name for R-507A is Genetron(R) AZ-50.

R-508 Series

V. P. Zhelezny, Y. V. Semenyuk, and V. N. Anisimov (Odessa State Academy of Refrigeration, Ukraine), **Liquid-Vapor Equilibria in R23/R116 System and its Thermodynamic Properties**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 453-458, July 1996 (6 pages with 1 figure and 3 tables, RDB6C30)

R-508 series, R-23/116, composition changes in azeotropic concentration from -93 to 12 °C, thermodynamic properties, thermophysical data

R-508A (R-508)

Klea 5R3 Physical Property Data Sheet, bulletin CP/10051/1Ed/33/994, ICI Klea, Runcorn, Cheshire, UK, October 1994 (6 pages with 3 tables, RDB5A09)

This bulletin provides summary property data and equations to calculate thermophysical properties for R-508A, an azeotropic blend containing R-23 and R-116 - specifically R-23/116 (39/61) - in metric (SI) units of measure. The bulletin tabulates physical properties including the atmospheric bubble and dew points, estimated critical parameters (temperature, pressure, and density), and latent heat of vaporization. It also indicates the bubble point pressure and latent heat of vaporization at -40 °C (-40 °F) and the saturated vapor density at 1 atmosphere (14.7 psia). The bulletin then presents a Martin-Hou equation of state and formulae to calculate the bubble, mid, and dew point temperatures for the saturation envelope. It also provides formulae for the latent heat of vaporization, ideal gas heat capacity, saturated liquid enthalpy, and liquid and vapor density, viscosity, and thermal conductivity. The document concludes with three tables giving calculated values for these properties at representative pressures of 100-2000 kPa (15-290 psia) and temperatures of -90 to -10 °C (-130 to 14 °F). ICI's product name for R-508A is Klea(R) 5R3.

Klea 5R3 Thermodynamic Property Data, SI Units, bulletin CP/10298/1Ed/33/1194, ICI Klea, Runcorn, Cheshire, UK, November 1994 (32 pages with 3 tables, RDB5A10)

This bulletin provides detailed thermodynamic properties for saturated and superheated R-508A, an azeotrope of R-23 and R-116 - specifically R-23/116 (39/61) - in metric (SI) units of measure. It comprises three tables, accompa-

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nied by notes on system performance with zeotropic blends and instructions to find the evaporator inlet and outlet temperatures based on expansion valve enthalpy and the evaporator pressure. The first presents saturation properties by pressure in 0.1 bar (10 kPa, 1.5 psi increments) for 100-2200 kPa (15-319 psia). The tabular data include the dew and bubble points as well as the liquid and vapor density, liquid and vapor enthalpy, and vapor entropy. The second table provides density, enthalpy, and entropy data for superheated vapor at constant pressure. The data span the range of 100-2200 kPa (15-319 psia) to temperatures as high as 98 °C (208 °F). The last table presents evaporator inlet temperatures as functions of pressure and enthalpy for 100-560 kPa (15-80 psia). ICI's product name for R-508A is Klea(R) 5R3.

Replacements for R-503: Klea(R) 5R3, bulletin TN06, ICI Klea, Wilmington, DE, undated circa 1995 (6 pages with 2 figures and 3 tables, RDB5A24)

This bulletin provides physical property and performance comparisons between R-503 and R-508A for very low temperature applications, such as medical storage and freeze drying. A table summarizes the compositions, boiling points and densities, latent heats of vaporization, critical parameters (temperature, pressure, and density), isentropic indices, flammabilities, and occupational exposure limits OELs) for the two azeotropes. Plots compare the vapor pressures and a set of tables contrast performance, based on simulated and experimental data. The bulletin concludes with a discussion of lubricants and materials compatibility, suggesting that R-508A generally can be used with the same materials as R-503. It notes that R-508A may be slightly less soluble than R-503, due to the lower solubility of R-116 compared to R-13, with polyalphaolefin (PAO), alkylbenzene (AB), and mineral oil (MO) lubricants. ICI's product name for R-508A is Klea(R) 5R3.

R-508B

D. B. Bivens, A. Yokozeki (E. I. duPont de Nemours and Company), and V. Z. Geller (Thermophysics Research Center), **Thermodynamic Properties of R23/116 Azeotropic Mixture**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 403-408, July 1996 (6 pages with 4 tables, RDB-6C14)

R-23/116 (46/54) [R-508B], PVT data: Martin-Hou equation of state (MH EOS), critical temperature, critical density; correlations for saturated bubble and dew point pressure, saturated liquid density, ideal gas heat capacity, saturated liquid and vapor density, saturated liquid and vapor entropy; experimental procedures

V. Z. Geller, V. P. Zhelezny (Thermophysics Research Center), D. B. Bivens, and A. Yokozeki (E. I. duPont de Nemours and Company), **Transport Properties and Surface Tension of R23/116 Azeotropic Mixture**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 397-402, July 1996 (6 pages with 1 figure and 3 tables, RDB6C13)

R-23/116 (46/54) [R-508B], viscosity, thermal conductivity, surface tension, correlations, experimental apparatus

Replacements for R-503 and R-13: Properties and Operating Characteristics of Suva(R) 95 Refrigerant, technical information bulletin ART-28 (H-60080-1), DuPont Chemicals, Wilmington, DE, April 1995 (2 pages with 2 tables, RDB5909)

This bulletin introduces R-508B, a 46:54 (by mass) blend of R-23 and R-116 previously identified as R-23/116 (46/54). It identifies potential applications as a replacement for R-13 and R-503 in very low temperature applications using cascaded compressors. The bulletin lists selected physical properties including the normal boiling point, corresponding latent heat of vaporization, critical temperature and pressure, and the saturated vapor density at -73.3 °C (-100 °F). It also indicates the ozone depletion potential (ODP) as zero, that the blend is nonflammable, and a recommended exposure limit. The bulletin outlines a performance comparison to R-13, R-23, and R-503 and provides a tabular summary of theoretical capacity, efficiency, and key operating parameters. The bulletin concludes by indicating that the components are listed both for TSCA in the United States and EINECS in Europe. DuPont's product name for R-508B is Suva(R) 95.

Thermodynamic Properties of Suva(R) 95 Refrigerant [R-508B (46/54)], technical Information report T-95-ENG (H-65138), DuPont Chemicals, Wilmington, DE, October 1995 (24 pages with 2 tables, RDB5C07)

This report provides thermodynamic property data for R-508B, a 46:54 (by mass) blend of R-23 and R-116 previously identified as R-23/116 (46/54). It lists selected physical properties including molecular weight, atmospheric boiling point, and critical parameters (temperature, pressure, density, and specific volume). It then presents a Martin-Hou (MH) equation of state (EOS) and an ideal gas heat capacity equation at constant pressure. It also supplies equations to calculate the liquid enthalpy, latent enthalpy (heat of vaporization), liquid entropy, vapor pressure, and density of the saturated liquid. The report provides tabular saturation properties (liquid and vapor pressure, volume, density, enthalpy, and entropy as well as latent heat of vaporization) for -123 to 13 °C (-190 to 55 °F). A set of tables presents volume, enthalpy, and entropy data for superheated vapor at constant pressure for 7-3800 kPa (1-550 psia). Most of the summary data and property equations are presented in both in metric (SI) and inch-pound (IP) units of measure, but the detailed saturation and superheat property tables are in IP units only. DuPont's product name for R-508B is Suva(R) 95.

Other Azeotropes

A-D. Leu and D. B. Robinson (University of Alberta, Canada), **High-Pressure Vapor-Liquid Equilibrium Phase Properties of the Octafluoropropane (K-218) - Chlorodifluoromethane (Freon-22) Binary System**, *Journal of Chemical and Engineering Data*, 37(1):7-10, January 1992 (4 pages, rdb8966)

summarizes determinations of the vapor-liquid equilibrium (VLE) compositions of R-22/218, a binary blend of R-22 and R-218, at 50, 60, 70, and 75 °C (122, 140, 158, and 167 °F): measurements were made at each temperature from the vapor pressures of the two pure components to the higher of the azeotropic or critical pressure for the blends; equilibrium ratios were calculated for each component at each temperature from the phase composition data; the azeotropic compositions and pressures were measured at 50, 65, and 70 °C (122, 149, and 158 °F); the critical pressures were determined at 70 and 75 °C (158 and 167 °F)

R-600 (Butane)

R. D. Goodwin, **Normal Butane: Provisional Thermodynamic Functions from 135 to 700 K at Pressures to 700 Bar**, report NBSIR 79-1621, National Institute of Standards and Technology (NIST, then the National Bureau of Standards, NBS), Gaithersburg, MD, September 1979 (available from GPO, rdb3946)

R-600, n-butane, thermodynamic properties, thermophysical data, equation of state (EOS)

M. B. Ewing, A. R. H. Goodwin, M. L. McGlashan, and J. P. M. Trusler, **Thermophysical Properties of Alkanes from Speeds of Sound Determined Using a Spherical Resonator - 2: n-Butane**, *Journal of Chemical Thermodynamics*, 20:243-256, 1988 (14 pages, rdb5110)

R-600, n-butane, thermodynamic properties, thermophysical data

W. M. Haynes and R. D. Goodwin, **Thermophysical Properties of Normal Butane from 135 to 700 K at Pressures to 70 MPa**, report NBS Technical Note 169, National Institute of Standards and Technology (NIST, then the National Bureau of Standards, NBS), Gaithersburg, MD, 1982 (available from GPO, rdb9131)

thermodynamic properties of R-600 (n-butane) for -138 to 427 °C (-217 to 800 °F) at pressures up to 70 MPa (10,150 psia); thermophysical data; equation of state (EOS)

R-600a (Isobutane)

T. R. Das, O. Reed, and P. T. Eubank, **PVT Surface and Thermodynamic Properties of Isobutane**, *Journal of Chemical and Engineering Data*, 18(3):-253-262, 1973 (10 pages, rdb5708)

R-600a, isobutane, thermodynamic properties, thermophysical data, equation of state (EOS)

R. D. Goodwin and W. M. Haynes, **Thermophysical Properties of Isobutane from 114 to 700 K at Pressures to 70 MPa**, report NBS Technical Note 1051, National Institute of Standards and Technology (NIST, then the National Bureau of Standards, NBS), Gaithersburg, MD, 1982 (available from GPO, rdb8250)

thermodynamic properties of R-600a (isobutane) for -159 to 427 °C (-254 to 800 °F) at pressures up to 70 MPa (10,150 psia); thermophysical data; equation of state (EOS)

J. M. H. Levelt Sengers, **Thermodynamic Properties of Isobutane in the Critical Region**, *Journal of Chemical and Engineering Data*, 28(4):354-362, 1983 (9 pages, rdb5714)

R-600a, thermophysical data

M. Waxman and J. S. Gallagher (National Institute of Standards and Technology, NIST), **Thermodynamic Properties of Isobutane for Temperatures from 250 to 600 K and Pressures from 0.1 to 40 MPa**, *Journal of Chemical and Engineering Data*, 28:224-241, 1983 (18 pages, rdb7724)

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thermodynamic properties of R-600a for -23 to 327 °C (-10 to 620 °F) and 100-4,000 kPa (15-580 psia); thermophysical data

R-704 (Helium)

S. Angus, K. M. de Reuck, and R. D. McCarty, **International Thermodynamic Tables of the Fluid State - 4: Helium**, International Union of Pure and Applied Chemistry (IUPAC), Pergammon Press, Oxford, UK, 1977 (RDB3950)

R-704 (helium), thermodynamic properties, thermophysical data, equation of state (EOS)

V. Arp, R. D. McCarty, and D. G. Friend, **Thermophysical Properties of Helium from 0.8 to 1500 K with Pressures to 2000 MPa**, NIST Technical Note 1334 (revised), National Institute of Standards and Technology (NIST), Gaithersburg, MD, August 1976 (available from GPO, rdb7A18)

R-704 (helium), thermodynamic properties, thermophysical data for -272 to 1227 °C (-458 to 2240 °F) to 2000 MPa (290,000 psia): equation of state (EOS), thermal conductivity, and viscosity

M. J. Slaman and R. A. Aziz, **Accurate Transport Properties and Second Virial Coefficients for Helium Based on a State-of-the-Art Interatomic Potential**, *International Journal of Thermophysics,* 12(5), 1991, with erratum in 16(4):1029-1030, July 1995 (rdb7A55)

R-704 (helium), transport properties, thermophysical data

R-717 (Ammonia)

J. Ahrends and H. D. Baehr (Universität Hannover, Germany) **Die thermodynamischen Eigenschaften von Ammontak** [The Thermodynamic Properties of Ammonia], research report 596, Verein Deutscher Ingenieure (VDI) [Association of German Engineers] Verlag, Düsseldorf, Germany, 1979 (in German, rdb6C36)

R-717, thermodynamic properties, thermophysical data

H. D. Baehr, H. Garnjost, and R. Pollak (Universität Hannover, Germany), **The Vapor Pressure of Liquid Ammonia: New Measurements above 328 K and a Rational Vapor-Pressure Equation** *Journal of Chemical Thermodynamics*, 8:113-119, 1976 (7 pages, rdb9702)

pressure-volume-temperature (PVT) properties of R-717, thermodynamic properties, thermophysical data

K. Date, **Studies of the P-V-T Relations of Fluids at High Pressure II. The P-V-T Relations of Ammonia in the Neighborhood of the Critical Point and the Critical Values of Ammonia**, *Review of Physical Chemistry of Japan*, 43:17-23, 1973 (7 pages, rdb9420)

pressure-volume-temperature (PVT) properties of R-717, thermodynamic properties, thermophysical data

T. A. Edison and J. V. Sengers (University of Maryland), **Thermodynamic Properties of Ammonia in the Critical Region**, *International Journal of Refrigeration*, 22(5):365-378, August 1999 (14 pages with 10 figures and 6 tables, RDB9701)

theoretically based, simplified crossover model to represent the thermodynamic properties of R-717 at 125-227 °C (257-440 °F): EOS was constructed so it can be used with that by Tillner-Roth et al. [see RDB7603] outside the critical region; compares results to earlier EOS by Haar and Gallagher [see RDB3207]

T. A. Edison and J. V. Sengers (University of Maryland), **Thermodynamic Properties of Ammonia in the Critical Region**, *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 177-202 (26 pages with 10 figures and 4 tables, RDB9819)

theoretically based, simplified crossover model to represent the thermodynamic properties of R-717: EOS was constructed so it can be used with that by Tillner-Roth et al. [see RDB7603] outside the critical region; compares results to earlier EOS by Haar and Gallagher [see RDB3207]

A. Fenghour, W. A. Wakeham, V. Vesovic, J. T. R. Watson (National Engineering Laboratory, UK), J. Millat, and E. Vogel (Universität Rostock, Germany), **The Viscosity of Ammonia**, *Journal of Physical and Chemical Reference Data*, 24(5):1649-1667, 1995 (19 pages, rdb7604)

R-717, transport properties, thermophysical data

A. V. Kletskii, T. I. Ryabusheva, N. S. Ershova, and L. P. Brul, **Isochoric Specific Heat of Ammonia**, *Kolloidnyi Tekhnika* [Refrigeration Technology], 8:22-24, 1973 (in Russian, rdb9513)

thermophysical properties of R-717 (ammonia)

R. Krauss (Universität Stuttgart, Germany), **Ammoniak** [Ammonia], *VDI-Wärmeatlas* [Thermal Atlas of the Association of German Engineers] (sixth edition), Verein Deutscher Ingenieure (VDI) Verlag, Düsseldorf, Germany, D/b:59-71, 1991 (13 pages, rdb3937)

heat transfer of R-717, thermal conductivity, transport properties, thermophysical data

R. A. Stairs and M. J. Sienko, **Surface Tension of Ammonia and of Solutions of Alkalai Halides in Ammonia**, *Journal of the American Chemical Society*, 78:920-923, 1956 (4 pages, rdb7948)

transport properties of R-717 (ammonia): thermophysical data

R. Tillner-Roth, F. Harms-Watzenberg, and H. D. Baehr (Universität Hannover, Germany), **Eine neue Fundamentalgleichung für Ammoniak** [A New Fundamental Equation for Ammonia], *DKV-Tagungsberichte*, Deutscher Kälte- und Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, 20:167-181, 1993 (15 pages in German, rdb7603)

R-717, equations of state (EOS), thermodynamic properties, thermophysical data

R. Tufeu, Ivanov, Garrabos, and B. Le Neindre (Universidade de Lisboa, Portugal), **Thermal Conductivity of Ammonia in a Large Temperature and Pressure Range Including the Critical Region**, *Berichte der Bunsengesellschaft für Physikalische Chemie*, 88:422-427, 1984 (6 pages, rdb7605)

transport properties of R-717 (ammonia): thermophysical data

R. Tufeu, A. Letaief, and B. Le Neindre (Universidade de Lisboa, Portugal), **Turbidity, Thermal Diffusivity, and Thermal Conductivity of Ammonia Along the Critical Isochore**, *Proceedings of the Eighth Thermophysical Properties Symposium* (Gaithersburg, MD, 15-18 June 1981), edited by J. V. Sengers, American Society of Mechanical Engineers (ASME), New York, NY, 1:451-457, 1982 (7 pages, rdb9512)

transport properties of R-717 (ammonia): thermophysical data

J. T. R. Watson (National Engineering Laboratory, UK), **The Dynamic Viscosity of Ammonia**, paper presented to Transport Formulations Subcommittee, International Union of Pure and Applied Chemistry (IUPAC), 1983 (rdb3936)

transport properties of R-717 (ammonia): thermophysical data

Ammonia Data Book, International Institute of Ammonia Refrigeration (IIAR), Washington, DC, 1993 (204 pages, RDB3635)

This comprehensive reference provides information on R-717 (ammonia) and most facets of its application. It covers general information on ammonia use and production. The book provides detailed thermodynamic, transport, and application data for use of ammonia in refrigeration systems. It also covers safety data, including hazardous and common reactions, compatibility, flammability, safety classifications, identified health hazards, and exposure consequences. The reference book covers environmental cycles for natural production and destruction of ammonia, detection methods, sampling, dispersion, and effects. It also addresses regulations for transportation and use of ammonia and identifies state emergency contacts.

Ammonia Used as a Refrigerant (L'ammoniac utilisé comme frigorigène), International Institute of Refrigeration (IIR), Paris, France, 1994 (available from the IIR for $22.00 plus postage, RDB4201)

R-717, thermophysical data

R-717 / 718 (Ammonia / Water as Refrigerant / Absorbent)

D. G. Friend, A. L. Olson, and A. Nowarski, **Standard Thermophysical Properties of the Ammonia + Water Binary Fluid**, *Physical Chemistry of Aqueous Systems: Meeting the Needs of Industry*, edited by H. J. White, Jr., J. V. Sengers, D. B. Neumann, and J. C. Bellows, Begell House Publishers, New York, NY, 854-861, 1995 (8 pages, rdb9507)

thermodynamic properties R-717 / 718 (ammonia/water), equation of state (EOS), thermophysical data

H. Garnjost, **Druck-Volumen-Temperaturmessungen mit Ammoniak und Wasser** [Pressure-Volume-Temperature Measurements of Ammonia and Water], PhD thesis, Universität Ruhr, Bochum, Germany, 1974 (in German, rdb9418)

thermodynamic properties of R-717 (ammonia) and R-718 (water); R-717 / 718; thermophysical data

N. C. Goomer et al., **Ammonia-Water Systems: Part I, Thermodynamic Properties**, Bhabha Atomic Research Center, Bombay, India, 1980 (rdb3235)

absorption, R-717, R-717/718, thermophysical data

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O. M. Ibrahim (University of Rhode Island) and S. A. Klein (University of Wisconsin), **Thermodynamic Properties of Ammonia-Water Mixtures**, *Transactions* (Winter Meeting, Chicago, IL, January 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(1):1495-1502, 1993 (8 pages, RDB8940)

presents an equation of state for R-717/718 (ammonia-water) mixtures: separate liquid and gas phase equations of state (EOSs) are provided for the pure ammonia and pure water; in the gas phase, the mixture is assumed to behave as an ideal solution, while in the liquid phase, the Gibbs excess energy is used to allow departure from ideal solution behavior; an existing correlation for the liquid Gibbs excess energy is modified to include experimental data at higher temperatures and pressures; the new correlation covers vapor-liquid equilibrium (VLE) pressures of 20 to 11,000 kPa (3-1600 psia) and temperatures of -43 to 327 °C (-46 to 620 °F); summarizes comparisons to published experimental data

P. C. Jain and G. K. Gable, **Equilibrium Property Data Equations for Aqua-Ammonia Mixtures**, paper 2180, *Transactions* (Semiannual Meeting, Philadelphia, PA, 24-28 January 1971), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 77(1):149 ff, 1971 (rdb3233)

R-717, ammonia, absorption, R-717, R-717/718, thermodynamic properties, thermophysical data

D. A. Kouremenos, S. K. Kakatsios, and O. E. Floratos, **Description of the Real Gas Isentropic Changes for an Ammonia-Water Vapor Mixture**, *Acta Mechanica*, 116(1-4):61-73, 1996 (13 pages, rdb6B08)

R-717/718 (ammonia-water binary mixture); calculated thermodynamic changes in the vapor phase for isentropic expansion starting at 800 °C (1472 °F) and initial pressures of 2,000, 3,000, 4,000, and 5,000 kPa (290, 435, 580, and 725 psia) with a computer program (ISENEXPR); thermodynamic relations used were obtained in terms of the Gibbs free energy equation for the gas phase of pure components; entropy was held constant; results are presented as diagrams showing the isentropic change of the gas phase mixture

R. A. Macriss, B. E. Eakin, R. T. Ellington, and J. Huebler, **Physical and Thermodynamic Properties of Ammonia-Water Mixtures**, research bulletin 34, Institute of Gas Technology (IGT), Chicago, IL, 1964 (rdb3232)

absorption, R-717, R-717/718, thermophysical data

J. W. Magee and N. Kagawa (National Institute of Standards and Technology, NIST), **Specific Heat Capacity at Constant Volume for {xNH_3 + (1x)H_2O} at Temperatures from 300 to 520 K and Pressures to 20 MPa**, *Journal of Chemical and Engineering Data,* 43(6):1082-1090, October 1998 (9 pages with 6 figures and 3 tables, RDB8C44)

measurements of the specific heat capacity (C_v) of R-717/718 (70/30), (80/20), and (90/10) with an adiabatic calorimeter for 27-245 °C (80-476 °F) and pressures of 3-20 MPa (435-2900 psia): measurements were made on both liquid and compressed gaseous samples of high purity; reports density measurements of the initial and final end points for each experiment

Y. M. Park (A-Joo University, Korea) and R. E. Sonntag (University of Michigan), **Thermodynamic Properties of Ammonia-Water Mixtures: A Generalized Equation-of-State Approach**, paper 3319, *Transactions (*Winter Meeting, Atlanta, GA, 10-14 February 1990), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 96(1), 1990 (10 pages with 9 figures and 3 tables, RDB3227)

absorption, R-717, R-717/718, thermophysical data

J. Patek and J. Klomfar (Academy of Sciences of the Czech Republic, Czechoslovakia), **Simple Functions for Fast Calculations of Selected Thermodynamic Properties of the Ammonia-Water System,** *International Journal of Refrigeration*, 18(4):228-234, May 1995 (7 pages, rdb8921)

presents a set of five equations that describe the vapor-liquid equilibria (VLE) properties of R-717/718 (ammonia/water) systems for design of absorption processes: the equations were constructed by fitting critically assessed experimental data to simple functional forms; they cover the region within which absorption cycles commonly operate; they calculate the enthalpy of the gas by an ideal-mixture approximation; presents the results as an enthalpy-concentration diagram

R. Tillner-Roth (Universität Hannover, Germany) and D. G. Friend, **Survey and Assessment of Available Measurements on Thermodynamic Properties of the Mixture (Water + Ammonia)**, *Journal of Physical and Chemical Reference Data,* 27:45-61, 1998 (17 pages, rdb8C45)

thermodynamic properties R-717/718 (ammonia/water), thermophysical data

R. Tillner-Roth (Universität Hannover, Germany) and D. G. Friend, **A Helmholtz Free Energy Formulation of the Thermodynamic Properties of the Mixture (Water + Ammonia)**, *Journal of*

Physical and Chemical Reference Data, 27:63-96, 1998 (34 pages, rdb8C46)

thermodynamic properties R-717/718 (ammonia/water), equation of state (EOS), thermophysical data

B. Ziegler and C. Trepp (Swiss Federal Institute of Technology, ETH, Switzerland), **Equation of State for Ammonia-Water Mixtures**, *International Journal of Refrigeration* (IJR), 7(2):101-106, February 1984 (6 pages, rdb3236)

absorption, R-717, R-717/718 EOS, thermodynamic properties, thermophysical data

Secondary Properties of Ammonia-Water Solutions, research project 1041-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1998 - 1999 (ASH-1041)

The contractor for the project is Kansas State University (KSU) at Manhattan, led by D. L. Fenton; it is sponsored by ASHRAE Technical Committee 10.1, Custom Engineered Refrigeration Systems.

R-718 (Water)

D. P. Fernández, Y. Mulev, A. R. H. Goodwin, and J. M. H. Levelt Sengers, **A Database for the Static Dielectric Constant of Water and Steam**, *Journal of Physical and Chemical Reference Data*, 24(1):-33-69, 1995 (37 pages, rdb8C47)

transport properties of R-718 (water); thermophysical data

L. Haar, J. S. Gallagher, and G. S. Kell, **NBS/NRC Steam Tables**, Hemisphere Publishing Corporation, Washington, DC, 1984 (rdb3938)

R-718, water, thermodynamic properties, thermophysical data, equation of state (EOS)

A. H. Harvey, **Thermodynamic Properties of Water: Tabulation from the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use**, report NISTIR 5078, National Institute of Standards and Technology, Boulder, CO, October 1998 (102 pages, available from NTIS, RDB8C35)

thermodynamic properties of R-718 (water); thermophysical data

A. H. Harvey, A. P. Peskin (National Institute of Standards and Technology, NIST), and S. A. Klein (University of Wisconsin), **NIST/ASME Steam Properties**, Standard Reference Database (SRD) 10 version 2.1, NIST, Gaithersburg, MD, 1997 (software and documentation available from NIST at srdata@nist.gov; RDB8C36)

thermodynamic properties of R-718 (water); thermophysical data

G. S. Kell, G. E. McLaurin, and E. Whalley, **PVT Properties of Water, VII: Vapor Densities of Light and Heavy Water from 150 to 500 °C**, *Proceedings of the Royal Society of London* A, UK, 425:49 ff, 1989 (rdb8C42)

thermodynamic properties of R-718 (water) for 150-500 °C (302-932 °F): thermophysical data

A. Pruß and W. Wagner, **New International Formulation for the Properties of Ordinary Water Substance for General and Scientific Use**, *Journal of Physical and Chemical Reference Data*, circa 1998 (rdb9908)

R-718 (water), thermodynamic properties, thermophysical data, equation of state (EOS)

M. L. V. Ramires, C. A. Nieto de Castro (Universidade de Lisboa, Portugal), Y. Nagasaka (Keio University, Japan), A. Nagashima, M. J. Assael (Aristotle University, Greece), and W. A. Wakeham (Imperial College, UK), **Standard Reference Data for the Thermal Conductivity of Water**, *International Journal of Thermophysics*, 24(3):1377-1381, 1995 (5 pages, rdb8C48)

transport properties of R-718 (water); thermophysical data

H. Sato (Keio University, Japan), K. Watanabe (Keio), J. M. H. Levelt Sengers (University of Maryland, USA), J. S. Gallagher (National Institute of Standards and Technology, NIST, USA), P. G. Hill, J. Straub (Technische Universität München, TUM, Germany), and W. Wagner, **Sixteen Thousand Evaluated Experimental Thermodynamic Property Data for Water and Steam**, *Journal of Physical and Chemical Reference Data*, 20(5):1023-1044, 1991 (22 pages, rdb7B31)

thermodynamic properties of R-718 (water); thermophysical data

A. Saul and W. Wagner, **A Fundamental Equation for Water Covering the Range from the Melting Line to 1273 K at Pressures up to 25 000 MPa**, *Journal of Physical and Chemical Reference Data*, 18(4):1537-1564, 1989 (28 pages, rdb7972)

R-718 (water): thermodynamic properties for melting to 1000 °C (1832 °F) and pressures up to 25,000 MPa (3.6 million psia), thermophysical data

J. V. Sengers and J. T. R. Watson (National Engineering Laboratory, UK), **Improved International**

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Formulations for the Viscosity and Thermal Conductivity of Water Substance, *Journal of Physical and Chemical Reference Data*, 15:1291-1322, 1986 (32 pages, rdb3939)

R-718, water, transport properties, thermophysical data

W. Wagner, A. Saul, and A. Pruß, **International Equations for the Pressure along the Melting and along the Sublimation Curve of Ordinary Water Substance**, *Journal of Physical and Chemical Reference Data*, 23(3):515-527, 1994 (13 pages, rdb7B34)

R-718 (water), thermodynamic properties, thermophysical data, equation of state (EOS)

Surface Tension of Water Substance, International Association for the Properties of Steam, 1975 (rdb3940)

R-718, water, transport properties, thermophysical data

R-718/LiBr (Water/Lithium Bromide as Refrigerant/Absorbent)

S. M. Jeter (Georgia Institute of Technology), J. P. Moran (CRS-Sirrine), and A. S. Teja (Georgia Institute of Technology), **Properties of Lithium Bromide/Water Solutions at High Temperatures and Concentrations - Part III: Specific**, paper 3556 (527-RP), *Transactions* (Winter Meeting, Anaheim, CA, 25-29 January 1992), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 98(1):137-149, 1992 (13 pages with 11 figures and 6 tables, RDB4435)

absorption, thermophysical data

J-L. Y. Lénard, S. M. Jeter, and A. S. Teja (Georgia Institute of Technology), **Properties of Lithium Bromide/Water Solutions at High Temperatures and Concentrations - Part IV: Vapor Pressure**, paper 3559 (527-RP), *Transactions* (Winter Meeting, Anaheim, CA, 25-29 January 1992), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 98(1):167-172, 1992 (6 pages with 5 figures and 3 tables, RDB4436)

absorption, thermodynamic properties, thermophysical data

L. A. McNeely, **Thermodynamic Properties of Aqueous Solutions of Lithium Bromide**, *Transactions,* American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 85(1):413 ff, 1979 (rdb3321)

absorption, thermodynamic properties, thermophysical data

M. R. Patterson, R. N. Crosswhite, and H. Perez-Blanco, **A Menu-Driven Program for Determining Properties of Aqueous Lithium Bromide Solutions**, report ORNL/TM-11331, Oak Ridge National Laboratory, Oak Ridge, TN, January 1990 (38 pages with program diskette, available from NTIS, RDB1147)

This report contains a description of and user's guide for the computer program LIMENU for calculating the thermodynamic and transport properties of aqueous solutions of lithium bromide (LiBr).

A. S. Teja, S. M. Jeter, R. J. Lee, R. M. Diguilio, J-L. Y. Lénard (Georgia Institute of Technology), and J. P. Moran (CRS-Sirrine), **Thermophysical Property Data for Lithium Bromide/Water Solutions at Elevated Temperatures**, final report for 527-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1991 (rdb4437)

absorption, thermodynamic properties, thermophysical data

Secondary Properties of Aqueous Lithium Bromide Solutions, research project 919-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, September 1996 - October 1997, extended to 1998 (ASH0919)

This research will catalog existing property data for mixtures of water and lithium bromide. It also will evaluate the feasibility of using these properties for control applications and assess available sensor technologies for them. The contractor for the project is the New Mexico Engineering Research Institute (NMERI) led by R. E. Tapscott; the project is sponsored by ASHRAE Technical Committee 8.3, *Absorption and Heat-Operated Machines.*

R-729 (Air)

H. D. Baehr and K. Schwier (Universität Hannover, Germany), **Die Thermodynamischen Eigenschaften der Luft** [The Thermodynamic Properties of Air], Springer-Verlag, Berlin, Germany, 1961 (in German, rdb8469)

thermodynamic properties of R-729 (air); thermophysical data

J. F. Ely and E. W. Lemmon, **Thermophysical Properties of Air and Air Component Mixtures (AIRPROPS),** Standard Reference Database (SRD) version 1.0, National Institute of Standards and Technology (NIST), Gaithersburg, MD, 1997 (software and documentation available from NIST, rdb-7A20)

R-728 (nitrogen), R-729 (air), R-732 (oxygen), and R-740 (argon), thermodynamic properties, thermophysical data: equation of state (EOS), thermal conductivity, viscosity, and others

K. Kadoya, N. Matsunaga, and A. Nagashima**, Viscosity and Thermal Conductivity of Dry Air In the Gaseous Phase**, *Journal of Physical and Chemical Reference Data*, 14(4):947-970, 1985 (24 pages, rdb9905)

viscosity of R-729 (air); transport properties; thermophysical data

E. W. Lemmon and S. G. Penoncello (University of Idaho), **The Surface Tension of Air and Air Component Mixtures,** *Advances in Cryogenic Engineering*, 39:1927-1934, 1994 (8 pages, rdb7A21)

R-728 (nitrogen), R-729 (air), R-732 (oxygen), and R-740 (argon): transport properties, thermophysical data, viscosity

R. T. Jacobsen, S. G. Penoncello, and S-J. Wei (University of Idaho), **The Development of New Correlations for the Transport Properties of Air at High Temperatures and Pressures**, National Institute of Standards and Technology (NIST), 1997 (rdb9910)

transport properties of R-729 (air); thermophysical data

R. T. Jacobsen, S. G. Penoncello (University of Idaho), S. W. Beyerlein, D. G. Friend, J. F. Ely, J. C. Rainwater, and W. M. Haynes (National Institute of Standards and Technology, NIST), **Thermophysical Properties of Air**, supplement to technical memorandum 1005, National Aeronautics and Space Administration (NASA) Langley Research Center, VA, 1995 (rdb7A75)

R-729 (air): thermodynamic and transport properties, thermophysical data, equation of state (EOS), thermal conductivity, viscosity, and others

R. T. Jacobsen, S. G. Penoncello, S. W. Beyerlein, W. P. Clarke, and E. W. Lemmon (University of Idaho), **Thermophysical Property Formulation for Air**, *Fluid Phase Equilibria*, 79:113-124, 1992 (12 pages, rdb9907)

R-729 (air): thermodynamic and transport properties, thermophysical data

K. Stephan and A. Laesecke (Universität Stuttgart, Germany), **The Thermal Conductivity of Fluid Air**, *Journal of Physical and Chemical Reference Data*, 14(1):227-234, 1985 (8 pages with 8 figures and 2 tables, RDB5531)

critical review of experimental data for the thermal conductivity of R-729 (air): recommended values for 100 kPa - 100 MPa (14.5-14,500 psia) and -203 to 727 °C (-334 to 1,340 °F): presents a derived equation of state (EOS), but notes the need for further measurements in the subcritical region; transport properties; thermophysical data

S-J. Wei, **The Development of New Correlations for the Transport Properties of Air at High Temperatures and Pressures**, thesis, University of Idaho, Moscow, ID, 1997 (rdb9909)

transport properties of R-729 (air); thermophysical data

R-744 (Carbon Dioxide)

S. Angus, B. Armstrong, and K. M. de Reuck, **International Thermodynamic Tables of the Fluid State - Carbon Dioxide**, International Union of Pure and Applied Chemistry (IUPAC), Pergammon Press, Oxford, UK, 1976 (rdb9218)

thermodynamic properties of R-744 (carbon dioxide): equation of state (EOS), thermophysical data

J. F. Ely, W. M. Haynes, and B. C. Bain, **Isochoric (PVT) Measurements on CO_2 and on (0.982 CO_2 + 0.018 N_2) from 250 to 330 K at Pressures to 35 MPa**, *Journal of Chemical Thermodynamics*, 21:879-894, 1989 (16 pages, RDB8C33)

thermodynamic properties of R-744 (carbon dioxide) and R-728/744 (1.8/98.2) for -23 to 57 °C (-10 to 134 °F) at pressures up to 35 MPa (5100 psia); thermophysical data

J. F. Ely, J. W. Magee, and W. M. Haynes, **Thermophysical Properties for Special High CO_2 Content Mixtures**, research report RR-110, Gas Processors Association, Tulsa, OK, 1987 (rdb3941)

R-744 (carbon dioxide) thermodynamic data: provides both a modified Benedict-Webb-Rubin (MBWR) equation of state (EOS) and a fundamental equation (FEQ, identified in the report as a Schmidt-Wagner EOS)

A. Fenghour, W. A. Wakeham, and V. Vesovic (Imperial College, UK), **The Viscosity of Carbon Dioxide**, *Journal of Physical and Chemical Reference Data*, 27(1):31-44, 1998 (14 pages, RDB9902)

viscosity of R-744 (carbon dioxide); transport properties; thermophysical data

please see page 6 for ordering information

R. Span and W. Wagner, **A New Equation of State for Carbon Dioxide Covering the Fluid Region from the Triple Point Temperature to 1100 K at Pressures up to 800 MPa**, *Journal of Physical and Chemical Reference Data,* 25(6):1509-1596, 1996 (88 pages, rdb8C49)

thermodynamic properties of R-744 from the triple point to 827 °C (1520 °F) and 800 MPa (116,000 psia), thermophysical data, equation of state (EOS)

V. Vesovic, W. A. Wakeham, G. A. Olchowy, J. V. Sengers, J. T. R. Watson, and J. Millat, **The Transport Properties of Carbon Dioxide**, *Journal of Physical and Chemical Reference Data,* 19(3):763-808, 1990 (45 pages, rdb3942)

transport properties of R-744: thermal conductivity, viscosity; thermophysical data

R-1150 (Ethene)

L. J. Van Poolen (National Institute of Standards and Technology, NIST, then the National Bureau of Standards, NBS), M. Jahangiri, and R. T. Jacobsen, **The Critical Liquid Volume Fraction Used to Represent and Predict Liquid-Vapor Coexistence Densities of Ethylene**, *Advances in Cryogenic Engineering,* 29:957 ff, 1984 (rdb9123)

thermodynamic properties of R-1150 (ethene); thermophysical data

R-1270 (Propene)

S. Angus, B. Armstrong, and K. M. de Reuck**, International Thermodynamic Tables of the Fluid State - 7: Propylene**, International Union of Pure and Applied Chemistry (IUPAC), Pergammon Press, Oxford, UK, 1980 (rdb3958)

thermodynamic properties of R-1270 (propene): equation of state (EOS), thermophysical data

Ethers

D. R. Defibaugh, K. A. Gillis, M. R. Moldover, G. Morrison, and J. W. Schmidt (National Institute of Standards and Technology, NIST), **Thermodynamic Properties of CHF_2-O-CHF_2, Bis(difluoromethyl) Ether**, *Fluid Phase Equilibria,* 81:285-305, 1992 (21 pages with 8 figures and 9 tables, RDB3327)

This paper reports on measurements and data reduction to provide thermodynamic property data for R-E134, a candidate alternative refrigerant. It summarizes measurements of the refractive index of the saturated liquid and vapor as well as the speed of sound of the dilute vapor. These measurements provide the normal boiling point, critical parameters (temperature, pressure, and density), and ideal gas heat capacity. Vapor pressure measurements using a high pressure ebulliometer are tabulated; the apparatus is depicted in a figure. Refractive index, speed-of-sound, results of acoustic isotherms, liquid density, and saturation data are tabulated; deviations with other measurements and data fits are plotted. Coefficients of a Carnahan-Starling-DeSantis (CSD) equation of state and a polynomial representation of the ideal gas heat capacity are derived and presented. The paper notes that samples of R-E134 with impurities were found to be unstable during laboratory measurements. It also notes that an azeotrope of R-E134 and R-143a was discovered during the investigation. Samples of R-E134 were found to be soluble in several elastomers used in the measurement apparatus.

J. J. Hurly, J. W. Schmidt, and K. A. Gillis (National Institute of Standards and Technology, NIST), **Virial Equation of State and Ideal-Gas Heat Capacities of Pentafluoro-Dimethyl Ether**, *International Journal of Thermophysics,* 18(1):137-159, January 1997 (23 pages with 3 figures and 3 tables, RDB-8910)

thermodynamic properties of R-E125; gas-phase equation of state (EOS) and ideal-gas heat capacity; measurements of the gas density with a Burnett apparatus and speed of sound by a cylindrical resonance apparatus; thermophysical data

M. Salvi-Narkhede, J. L. Adcock, A. Gakh, and W. A. Van Hook (University of Tennessee), **Vapor Pressures, Liquid Molar Volumes, Vapor Non-Ideality, and Critical Properties of $CF_3OCF_2CF_2CF_3$, c-$CF_2CF_2CF_2CF_2O$, CF_3OCF_2O-CF_3, $CF_3OCF_2CF_2H$**, *Journal of Chemical Thermodynamics,* 25:643-647, 1993 (5 pages, rdb4445)

$CF_3CF_2CF_2OCF_3$, R-CE318 (c-$CF_2CF_2CF_2OCF_2$), R-E218ca12 ($CF_3OCF_2OCF_3$), R-E227ca2 ($CHF_2CF_2OCF_3$), thermodynamic properties, thermophysical data

M. Salvi-Narkhede, B-H. Wang, J. L. Adcock, and W. A. Van Hook (University of Tennessee), **Vapor Pressures, Liquid Molar Volumes, Vapor Non-Ideality, and Critical Properties of Some Partially Fluorinated Ethers ($CF_3OCF_2CF_2H$, CF_3OCF_2H, and CF_3OCH_3), Some Perfluoroethers (CF_3O-CF_2OCF_3, c-$CF_2OCF_2OCF_2$, and c-$CF_2CF_2CF_2$-**

O), and of CHF_2Br and CF_3CHFCF_3, *Journal of Chemical Thermodynamics*, 24:1065-1075, 1992 (11 pages with 2 figures and 7 tables, RDB3728)

thermodynamic properties of R-22B1, R-227ea, R-E125, R-E143a, R-E218ca, and R-E227ca2; thermophysical data

T. Tsuge, H. Sato, and K. Watanabe (Keio University, Japan), **Thermodynamic Properties and Cycle Performance of a New Alternative Refrigerant, HFE-245mc**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 17-25, November 1997 (9 pages with 6 figures and 2 tables, RDB8321)

thermodynamic properties of R-E245cb1 (identified in the paper as "HFE-245mc"), a proposed replacement for R-114 in high-temperature heat pumps: pressure-volume-temperature (PVT) properties and vapor pressures; thermophysical data; virial equation of state (EOS); performance comparisons with R-114 based on cycle analyses; concludes that use of R-E245cb1 is feasible, though the comparisons show its coefficient of performance (COP) to be 4-10% lower

B-H. Wang, J. L. Adcock, S. B. Mathur, and W. A. Van Hook (University of Tennessee), **Vapor Pressures, Liquid Molar Volumes, Vapor Non-Idealities, and Critical Properties of Some Fluorinated Ethers: $CF_3OCF_2OCF_3$, $CF_3OCF_2CF_2H$, c-CF_2-CF_2CF_2O, CF_3OCF_2H, and CF_3OCH_3; and of CCl_3F and CF_2ClH**, *Journal of Chemical Thermodynamics*, 23:699-710, December 1991 (12 pages with 8 tables, RDB2505)

Vapor pressures, compressibilities, expansivities, and molar volumes of the liquid phase are presented, based on measurements between room temperature and the critical temperature, for a series of fluorinated ethers. Critical temperatures and pressures and approximate melting and boiling temperatures are tabulated for R-E218ea12 (perfluorodimethoxymethane), R-E227ca2 (2-hydryl-F-ethyl F-methyl ether), R-CE216 (F-oxetane), and R-E125 (pentafluorodimethyl ether). These ethers are under investigation as potential refrigerants, blowing agents, and cleaning agents based on their physical and chemical similarity to present refrigerants. Equations are presented for determination of these properties. Vapor-phase nonidealities were measured for each compound, but only for samples of high vapor density. Apparatus calibrations were verified with measurements for R-11 and R-22.

L. A. Weber and D. R. Defibaugh (National Institute of Standards and Technology, NIST), **Vapor Pressure of Pentafluorodimethyl Ether**, *Journal of Chemical and Engineering Data*, 41(3):382-385, 1996 (4 pages with 1 figure and 4 tables, RDB8218)

thermodynamic properties of R-E125; measurements of vapor pressures from -45 to 58 °C (-49 to 136 °F); extrapolations to lower temperatures; determination of the normal boiling point (-35.09 °C, -31.16 °F); thermophysical data

General and Multiple Fluids

A. G. Asambaev, **The Heat Conduction of the Liquid and Gas Refrigerants and Their Solutions - Alternatives of Chlorofluorocarbons**, PhD dissertation, LTIHP, Russia, 1992 (rdb5447)

transport properties of R-123, R-125, and R-134a: thermal conductivity, thermophysical data

M. J. Assael, J. H. Dymond, and S. K. Polimatidou (Aristotle University, Greece), **Correlation and Prediction of Dense Fluid Transport Coefficients. VII. Refrigerants**, *International Journal of Thermophysics,* 16:761-772, 1995 (12 pages, rdb-8221)

transport properties, thermophysical data

M. J. Assael and S. K. Polimatidou (Aristotle University, Greece), **Measurements of the Viscosity of Liquid R22, R124, and R125 in the Temperature Range 273-333 K at Pressures up to 17 MPa**, *International Journal of Thermophysics*, 15(5):779-790, 1994 (12 pages, rdb7831)

transport properties R-22, R-124, and R-125: measurements for 0-60 °C (32-140 °F) and up to 17 MPa (2500 psia); thermophysical data

M. J. Assael, S. K. Polimatidou (Aristotle University, Greece), E. Vogel (Universität Rostock, Germany), and E. Wakeham (Imperial College, UK), **Measurements of the Viscosity of R11, R12, R141b, and R152a in the Temperature Range 270-340 K at Pressures up to 20 MPa**, *International Journal* of *Thermophysics,* 15(4):575-590, 1994 (16 pages, rdb7832)

transport properties for R-11, R-12, R-141b, and R-152a: measurements for -3 to 67 °C (26-152 °F) and up to 20 MPa (2900 psia); thermophysical data

M. J. Assael, J. H. Dymond, and S. K. Polimatidou (Aristotle University, Greece), **Measurements of the Viscosity of R134a and R32 In the Temperature Range 270-340 K at Pressures up to 20**

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MPa, *International Journal of Thermophysics,* 15(4):591-602, 1994 (12 pages, rdb7833)

transport properties for R-32 and R-134a: measurements for -3 to 67 °C (26-152 °F) and up to 20 MPa (2900 psia); thermophysical data

M. J. Assael and L. Karagiannidis (Aristotle University, Greece), **Measurements of the Thermal Conductivity of R22, R123, and R134a in the Temperature Range 250-340 K at Pressures up to 30 MPa**, *International Journal of Thermophysics,* 14(2):183-197, 1993 (15 pages, rdb4968)

transport properties of R-22, R-123, and R-134a: measurements for -23 to 67 °C (-10 to 152 °F) and pressures up to 30 MPa (4350 psia); thermophysical data

M. J. Assael, L. Karagiannidis, and S. K. Polimatidou (Aristotle University, Greece), **Measurements of the Thermal Conductivity of R22, R123, R134a, and R152a**, *High Temperatures - High Pressures*, 25:259-267, 1993 (9 pages, RDB9141)

transport properties of R-22, R-123, R-134a, and R-152a; thermophysical data

M. J. Assael, J. H. Dymond, M. Papadaki, and P. M. Patterson, **Correlation and Prediction of Dense Fluid Transport Coefficients. I. n-Alkanes**, *International Journal of Thermophysics,* 13:269-281, 1992 (13 pages, rdb8219)

transport properties, thermophysical data

M. J. Assael, J. H. Dymond, M. Papadaki, and P. M. Patterson, **Correlation and Prediction of Dense Fluid Transport Coefficients. III. n-Alkane Mixtures**, *International Journal of Thermophysics,* 13:659-669, 1992 (11 pages, rdb8220)

transport properties, thermophysical data

H. D. Baehr and R. Tillner-Roth (Universität Hannover, Germany), **Thermodynamische Eigenschaften umveltvertraglicher Kältemittel: Zustandsgleichungen and Tafeln für Ammoniak, R 22, R 134a, R 152a and R 123** [Thermodynamic Properties of Environmentally Acceptable Refrigerants: Equations of State and Tables for Ammonia, R22, R134a, R152a, and R123], Springer-Verlag, Berlin, Germany, 1995 (191 pages in German with English preface, rdb6AA1)

thermodynamic properties of R-22, R-123, R-134a, R152a, and R-717: equations of state (EOS); vapor pressure; thermophysical data

V. G. Baidakov and I. I. Sulla, **Surface Tension of Propane and Isobutane at Near-Critical Temperatures**, *Russian Journal of Physical Chemistry*, Russia (then USSR), 59:551-554, 1985 (4 pages, rdb7953)

transport properties of R-290 (propane) and R-600a (isobutane); thermophysical data

W. Beckermann and F. Kohler, **Acoustic Determination of Ideal-Gas Heat Capacity and Second Virial Coefficients of Some Refrigerants between 250 and 420 K**, *International Journal of Thermophysics*, 16:455-464, 1995 (10 pages, rdb8251)

thermodynamic properties of R-143a and others: derivation of the second virial coefficients and ideal gas heat capacities form acoustic measurements at -23 to 147 °C (-10 to 296 °F); thermophysical data

O. V. Beljajeva, A. J. Grebenkov, and B. D. Timofejev (Academy of Sciences, Minsk, Belarus), **Sound Velocity in Refrigerants R125, R218, and R134a/152a**, *Vestn*. *Mezhduna. Akad. Holoda*, Russia, 1998(1):26-27, 1998 (2 pages with 5 tables, in Russian, rdb9311)

transport properties of R-125, R-218, and R-134a/152a; thermophysical data

A. L. Beyerlein (Clemson University, USA), D. D. DesMarteau (Clemson), K. N. Naik (Xerox Research Center, Canada), and Y. Xie (Clemson University), **Physical Properties of Fluorinated Propane and Butane Derivatives and the Vapor Pressure of R-245ca/338mccq Mixtures as R-11 Alternatives**, paper 3968, *Transactions* (Winter Meeting, Atlanta, GA, 17-21 February 1996), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 102(1):358-366, 1996 (9 pages with 3 figures and 6 tables, RDB8211)

R-245eb, R-254ca, R-254fb, R-338mcf (identified in the paper as R-338mcfm), R-347mec (R-347mecq), R-356mff (R-356mffm), R-356mec (R-356mecs), R-356mmz (R-356mms), R-245ca/-338mcc (R-245ca/338mccq)

A. L. Beyerlein, D. D. DesMarteau, S. H. Hwang (Clemson University), N. D. Smith (Environmental Protection Agency, EPA), and P. Joyner (Electric Power Research Institute, EPRI), **Physical Properties of Fluorinated Propane and Butane Derivatives as Alternative Refrigerants**, paper 3658, *Transactions* (Winter Meeting, Chicago, IL, January 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(1):368-379, 1993 (12 pages with 10 tables, RDB3408)

C. M. Bignell and P. J. Dunlop, **Second Virial Coefficients for Seven Fluoroethanes and Interaction Second Virial Coefficients for their Binary Mixtures with Helium and Argon**, *Journal of Chemical and Engineering Data,* 38:139-140, 1993; republished as *Journal of Chemical Physics,* 98:4889-4891, 1995 (2/3 pages, RDB8203) thermodynamic properties of R-32, R-143a, and others; virial coefficients derived from pressure-volume-temperature (PVT) measurements; thermophysical data

D. B. Bivens and A. Yokozeki (DuPont Fluoroproducts), **Heat Transfer Coefficients and Transport Properties for Alternative Refrigerants**, *Proceedings of the 1994 International Refrigeration Conference at Purdue,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 299-304, July 1994 (6 pages with 4 figures and 1 table, RDB4837)

R-22, R-404A, R-32/125 (60/40), R-32/125/134a (30/10/60), R-32/134a, R-502, thermophysical data

D. B. Bivens, A. Yokozeki (DuPont Chemicals), V. Z. Geller, and M. E. Paulaitis (University of Delaware), **Transport Properties and Heat Transfer of Alternatives for R-502 and R-22**, *R-22 and R-502 Alternatives* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 19-20 August 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 73-84, 1994 (12 pages with 16 figures and 12 tables, RDB4521)

thermophysical data

W. L. Blindenbach, I. G. Economou, P. G. Smits, C. J. Peters, and J. de Swaan (Delft University of Technology, The Netherlands), **Modeling the Thermodynamic Properties of CFC and HCFC Compounds, and the Vapor-Liquid Equilibria of CFC and HCFC Mixtures and CFC/HCFC-Hydrocarbon Mixtures, with the Perturbed Anisotropic Chain Theory (PACT**), *Fluid Phase Equilibria*, 97:13-28, 15 June 1994 (16 pages, rdb8930)

presents a model to calculate the vapor pressure and liquid density of single compound refrigerants and the vapor-liquid equilibria (VLE) of binary and ternary mixtures over a wide range of temperature and pressure: it is identified as the *Perturbed Anisotropic Chain Theory* (PACT) model; it was developed for chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants as well as blends of them or with hydrocarbon (HC) components; demonstrates the model with predictions for nineteen binary and three ternary blends and comparisons to experimental data and to the widely used Peng-Robinson (PR) and Soave-Redlich-Kwong (SRK) equations of state (EOSs); indicates that the overall deviation between these cubic equations predictions and experimental data is twice the deviation for PACT predictions; also indicates that excellent correlation of the experimental data is obtained using an added temperature independent, binary adjustable parameter

C. Bouchot and D. Richon (École Nationale Supérieure des Mines de Paris, France), **P.V.T. and V.L.E. Properties of Several Refrigerants (Pure Compounds and Mixtures) Through an Original Apparatus**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:88-95, 1995 (8 pages with 3 figures and 5 tables, rdb-7729)

thermodynamic properties, thermophysical data, design and use of a vibrating tube densimeter measure the properties of R-404A and calibration with R-744 (carbon dioxide)

J. M. Calm (Engineering Consultant) and G. C. Hourahan (Air-Conditioning and Refrigeration Technology Institute (ARTI), **Physical, Safety, and Environmental Data for Refrigerants**, *Heating/Piping/Air Conditioning Engineering* (HPAC), 71(8):-27-33, August 1999 (7 pages with 1 figure and 2 tables, available from JMC as RDB9901)

This paper presents tabular summaries of selected physical, safety, and environmental (atmospheric lifetime, ozone depletion potential, ODP, global warming potential, GWP) data for 135 alternative and candidate refrigerants, including blends, along with comparative information for those that have been or are being replaced. The alternatives include both those in commercial production or development and a number that are still being evaluated, such as hydrofluoroethers and fluorinated amines. The two tables, one sorted by designation and the other by normal boiling point (NBP), provide data in both metric (SI) and inch-pound (IP) units for a total of 186 compounds and blends. The paper also discusses the parameters, indicating both their significance and reasons for apparent discrepancies in published studies.

H. B. Chae, J. W. Schmidt, and M. R. Moldover (National Institute of Standards and Technology, NIST), **Surface Tension of Refrigerants R-123 and R-134a**, *Journal of Chemical and Engineering Data,* 35(1):6-8, January 1990 (3 pages with 2 figures and 3 tables, available from JMC as RDB0917)

The surface tensions of two environmentally acceptable refrigerants (R-123 and R-134a) were measured with a differential capillary rise technique. Measurements span the temperature range -25 to 140 °C (-13 to 284 °F) for R-123 and -10 to 95 °C (14 to 203 °F) for R-134a.

H. B. Chae, J. W. Schmidt, and M. R. Moldover (National Institute of Standards and Technology, NIST), **Alternative Refrigerants R-123a, R-134, R-141b, R-142b, and R-152a: Critical Temperature, Refractive Index, Surface Tension, and Estimates of Liquid, Vapor, and Critical Densities**,

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Journal of Physical Chemistry, 94(25):8840-8845, 13 December 1990 (6 pages with 6 figures and 4 tables, RDB0918)

Differential capillary rise and refractive index data are reported for five alternative refrigerants: R-123a, R-134, R-141b, R-142b, and R-152a. This paper explains the selection of these fluids, describes the apparatus and analytical methods, and compares the findings with published reports by others. The data extend from approximately 25 °C (77 °F) to the critical point of each fluid and directly yield the critical temperature T_c and the temperature-dependent capillary length. The present data were combined with liquid density data (near ambient temperature) to determine the Lorentz-Lorenz constant. The Lorentz-Lorenz relation is used to estimate the liquid, vapor, and critical densities, and the surface tension. R-141b slowly decomposed when maintained near its critical point (in contact with gold, sapphire, stainless steel, and crown glass).

A. C. Cleland, **Computer Subroutines for Rapid Evaluation of Refrigerant Thermodynamic Properties**, *International Journal of Refrigeration* (IJR), 9:346-351, November 1986 (6 pages, rdb9928)

simulation, thermodynamic properties, thermophysical data

S. Corr, J. D. Morrison, and F. T. Murphy (ICI Chemicals and Polymers, Limited, UK), **An Evaluation of the Effects of Lubricants on the Thermodynamic Properties and Performance of Refrigerant Mixtures in Refrigeration and Air Conditioning Cycles**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 119-124, July 1996 (6 pages with 11 figures, RDB6821)

thermodynamic model based on the Wilson-MHV-2 methodology; property prediction for tetrary blends of R-32, R-125, R-134a, and a mixed-acid polyolester (POE) lubricant; vapor-liquid equilibria (VLE) behavior of refrigerant-lubricant mixtures; the effects of the oil are expected to be small, but may increase for those points in the cycle that are close to the dew point line of the oil-free refrigerant

B. de Vries, **Thermodynamischen Eigenschaften von der alternativen Kältemittel R32, R125, und R143a - Messungen and Fundamentalgleichungen** [Thermodynamic Properties of R-32, R-125, and R-143a - Measurements and Fundamental Equations], Doktor-Ingenieur [Doctor of Engineering] thesis, Universität Hannover, Hannover, Germany, 1996; *DKV-Forschungsberichte* [Research Report] 55, Deutscher Kälte- and Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Stuttgart, Germany, 1997 (in German, rdb8302)

thermodynamic properties of R-32, R-125, and R-143a: fundamental equation (FEQ); thermophysical data

D. R. Defibaugh and M. R. Moldover (National Institute of Standards and Technology, NIST), **Compressed and Saturated Liquid Densities for 18 Halogenated Organic Compounds**, *Journal of Chemical and Engineering Data*, 42(1):160-168 plus 3 page errata, January 1997 (12 pages with 8 figures and 5 tables, available from JMC as RDB7713)

measurements of the liquid pressure-density-temperature behavior, using a vibrating tube densimeter, of R-11, R-22, R-123, R-123a, R-124, R-E125, R-134, R-134a, R-141b, R-143, R-143a, R-152a, R-218, R-227ea, R-245cb, R-245fa R-E245fa1 (identified in the document as E245), and R-290 (propane), thermodynamic properties, thermophysical data, correlations using the modified Benedict-Webb-Rubin (MBWR) equations of state (EOS)

D. R. Defibaugh and G. Morrison (National Institute of Standards and Technology, NIST), **Interaction Coefficients for 15 Mixtures of Flammable and Non-flammable Components**, *International Journal of Refrigeration* (IJR), 18(8):518-523, November 1995 (6 pages with 2 figures and 2 tables, RDB7955)

Bubble pressures were measured for 15 binary blends, most consisting of one flammable and one nonflammable component. The refrigerants examined were R-11/601a (R-11/isopentane), R-32/125 (R-410 series), R-32/134a, R-123/141b, R-125/143a (R-507 series), R-134a/152a, R-134a/601a (R-134a/isobutane), R-C270/134a (cyclopropane/R-134a), R-290/134a (propane/-134a), and R-601a/123. Also studied were mixtures of R-32/152a, R-152a/600, R-152a/600a, R-C270/-152a, and R-290/152a which comprise two flammable components. The measurements were made at approximately equimolar compositions using either a vapor-liquid equilibria (VLE) apparatus, over a range of temperatures, or a static pressure measurement at 0 °C (32 °F). The bubble pressures were used to determine interaction coefficients that characterize the non-ideal behavior of these fluid mixtures. The resulting interaction coefficients were incorporated into REFPROP 4.01 and the calculated bubble pressures were compared to those measured. The interaction coefficients and comparisons are tabulated.

D. D. DesMarteau (Clemson University) and A. L. Beyerlein (Clemson University), **New Chemical Alternatives for the Protection of Stratospheric Ozone,** report EPA-600/R-95-113, U.S. Environmental Protection Agency (EPA), Research Triangle Park, NC, 1995 (rdb8216)

R-245cb and others, thermodynamic properties, thermophysical data

S. Devotta and V. R. Pendyala (National Chemical Laboratory, India), **Prediction of Volumetric and Thermodynamic Properties of Refrigerants: A Simplified Procedure,** *International Journal of Refrigeration* (IJR), 17(2):94-100, 1994 (8 pages, rdb-9142)

simplified prediction of refrigerant properties for R-123, R-134a, and others; thermophysical data

D. E. Diller, A. S. Aragon, and A. Laesecke (National Institute of Standards and Technology, NIST), **Measurements of the Viscosities of Saturated and Compressed Liquid 1,1,1,2-Tetrafiuoroethane (R134a), 2,2-Dichloro-1,1,1-trifluoroethane (R123), and 1,1-Dichloro-1-fluoroethane (R141b),** *Preprints of the 11th Symposium on Thermophysical Properties* (Boulder, CO, 23-27 June 1991), American Society of Mechanical Engineers (ASME), New York, NY; republished in *Fluid Phase Equilibria*, 88:251-262, 1993 (12 pages with 10 figures and 6 tables, RDB3922)

transport properties of R-123, R-134a, and R-141b: presents shear viscosity measurements taken with a torsional crystal viscometer for the saturated and compressed liquids between -103 and 47 °C (-154 and 116 °F) and pressures to 30 MPa (4,350 psia); presents correlations with an empirical fluidity-volume-temperature equation and comparisons to prior studies by other researchers; thermophysical data

D. E. Diller and S. M. Peterson (National Institute of Standards and Technology, NIST), **Measurement of the Viscosities of Saturated and Compressed Fluid 1-Chloro-1,2,2,2-tetrafiuoroethane (R124) and Pentafluoroethane (R125) at Temperatures Between 120 and 420 K,** *International Journal of Thermophysics,* 14(1):55-66, January 1993 (12 pages with 8 figures and 4 tables, RDB4A60)

measurements of the shear viscosities for R-124 and R-125 at -153 to 147 °C (-244 to 296 °F) with two torsional crystal viscometers; notes that the fluidity (reciprocal of viscosity) increases linearly with molar volume at fixed temperature and weakly with temperature at fixed volume for small molar volumes; provides correlations for the measured data and comparisons to findings in other studies; transport properties, thermophysical data

P. A. Domanski and D. A. Didion, **Impact of Refrigerant Property Uncertainties on Prediction of Vapor Compression Cycle Performance,** report NBSIR 86-3373, National Institute of Standards and Technology (NIST, then the National Bureau of Standards, NBS), Gaithersburg, MD, December 1986 (54 pages, rdb0922)

This paper presents a sensitivity study of a vapor-compression cycle in the form of a heat pump operating in the cooling mode. The study was performed with the aid of a detailed simulation model; runs were made for different parametric values and the capacity and power input were compared with results of a run using an unchanged value of the parameters. The effects on evaporator and condenser pressures, and refrigerant mass flow rate are given. The independent variables Include thermodynamic and transport properties, as well as the refrigerant flow, heat transfer, and pressure drop coefficients. The parameters which had the most effect on system performance were liquid transport properties, evaporative heat transfer coefficient, and vapor density.

R. Döring (Fachhochschule Münster, Germany), **Thermodynamic Properties of the Refrigerants R 134a (CH_2F-CF_3) and R 123 ($CHCl_2$-CF_3)**, *Thermophysical Properties of Pure Substances and Mixtures for Refrigeration* (proceedings of the meeting of IIR Commission B1, Herzlia, Israel, March 1990), International Institute of Refrigeration (IIR), Paris, France, 57-68, 1990 (12 pages with 7 figures, RDB5621)

R-123, R-134a, thermodynamic properties, thermophysical data

R. Döring (Fachhochschule Münster, Germany) and H. Buchwald (Kali-Chemie AG, Germany), **Experimentelle und theoretische Untersuchungen der Kältemittel R 134a (CH_2F-CF_3) und R 123 ($CHCl_2$-CF_3)** [Experimental and Theoretical Investigations of Refrigerants R-134a (CH_2FCF_3) and R 123 ($CHCl_2CF_3$)], *Ki Klima-Kälte-Heizung*, Germany, 18(3):108-112, 1990 (5 pages with 7 figures and 7 tables, in German, RDB5220)

thermodynamic properties, thermophysical data

R. Döring (Fachhochschule Münster, Germany) and H. Buchwald (Kali-Chemie AG, Germany), **Thermodynamische Eigenschaften der Kältemittel R 134a (CH_2F-CF_3) und R 123 ($CHCl_2$-CF_3)** [Thermodynamic Properties of Refrigerants R-134a (CH_2FCF_3) and R-123 ($CHCl_2CF_3$)], *Bericht über die Kälte-Klima-Tagung* [Proceedings of the Refrigeration and Air-Conditioning Conference] (Hannover, Germany, 22 November 1989), Deutscher Kälte- und Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, 16(2):225-246,

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1989 (24 pages with 8 figures and 4 tables, in German, rdb5221)

equations of state (EOS) and thermodynamic properties for R-123 and R-134a; thermophysical data

D. C. Dowdell and G. P. Matthews, **Gas Viscosities and Intermolecular Interactions of Replacement Refrigerants HCFC-123 (2,2-Dichloro-1,1,1-trifluoroethane), HCFC-124 (2-Chloro-1,1,1,2-tetrafluoroethane), and HFC-134a (1,1,1,2-Tetrafluoroethane)**, *Journal of the Chem. Society - Faraday Transactions*, London, UK, 89(19):3545-3552, 1993 (8 pages, rdb7C59)

R-123, R-124, and R-134a: thermodynamic and transport properties, thermophysical data, Lennard-Jones parameters

D. C. Dowdell and G. P. Matthews, **Gas Viscosities and of HCFC 123, HCFC 124, and HFC 134a**, *Ericeira* (proceedings of the Ozone Protection Workshop), 1992 (rdb9143)

R-123, R-124, and R-134a: thermodynamic and transport properties, thermophysical data

H. A. Duarte-Garza (Texas A&M University), C-A. Hwang (Quantum Chemical Corporation), R. C. Miller (Washington State University), B. E. Gammon, K. N. Marsh, K. R. Hall, and J. C. Holste (Texas A&M University), **Thermodynamic Properties of Pentafluoroethane (R-125) and 1-1-Dichioro-1-fluoroethane (R-141b)**, paper DE-93-6-3 (654-RP), *Transactions* (Annual Meeting, Denver, CO, June 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(2):649-664, 1993 (16 pages with 10 figures and 9 tables, RDB3618)

measurements of the vapor pressures, liquid densities, and vapor densities were for R-125 and R-141b at temperatures between -93 and 207 °C (-135 and 400 °F) and pressures to 70 MPa (10,000 psia); presents the measured critical temperature and derived critical pressure for each fluid; also presents correlations for the measured properties; summarizes enthalpies and entropies for the saturated liquid, saturated and superheated vapor, and the heat capacities of saturated liquid and vapor derived for R-125 from the PVT behavior and ideal gas heat capacities

A. E. Elhassen, R. J. B. Craven, and K. M. de Reuck (Imperial College, London, UK), **Comparisons of Equations of State with Experimental Data for R-134a and R-123**, report HPP-AN18-3 for IEA HPC Annex 18, International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, April 1993; republished in 1995 (45 pages, rdb7960)

single-phase and saturation properties for R-123 and R-134a; equations of state (EOS); thermodynamic properties; thermophysical data

J. F. Ely, **A Predictive Exact Shape Factor Extended Corresponding States Model for Mixtures**, *Advances in Cryogenic Engineering*, 35:217-292 (possibly 35:1511-1520), 1990 (13 pages, rdb8902

transport properties, thermophysical data

J. F. Ely and H. J. M. Hanley, **Prediction of Transport Properties**, *Industrial Engineering Chemistry Fundamentals,* 20:323-332, 1981 (10 pages, rdb-8903)

transport properties, thermophysical data

G. Ernst and J. Busser, **Ideal and Real Gas State Heat Capacities C_P of C_3H_8 and i-C_4H_{10}**, *Journal of Chemical Thermodynamics*, 2:787 ff., 1970 (rdb-5709)

R-290 (propane), R-600a (isobutane), thermodynamic properties, thermophysical data

B. R. Fellows, R. G. Richard, and I. R. Shankland (AlliedSignal Incorporated), **Electrical Characterization of Alternate Refrigerants**, paper 45, *New Challenges in Refrigeration* (proceedings of the XVIllth International Congress of Refrigeration, Montreal, Québec, Canada, 10-17 August 1991), International Institute of Refrigeration (IIR), Paris, France, II:398-402, August 1991 (5 pages with 2 figures and 7 tables, 10 page reprint available from JMC as RDB2319)

R-11, R-12, R-22, R-32, R-114, R-115, R-123, R-123a, R-124, R-125, R-134, R-134a, R-141b, R-142b, R-143a, R-152a, R-C318, R-502, R-7146; breakdown voltage, dielectric and resistivity data

B. R. Fellows, R. G. Richard, and I. R. Shankland (AlliedSignal Incorporated), **Thermal Conductivity Data for Some Environmentally Acceptable Fluorocarbons**, *Thermal Conductivity*, Plenum Press, New York, NY, 21:311-325, 1990 (15 pages, rdb-8459)

transport properties of R-123 and others; thermophysical data

M. Fermeglia, A. Bertucco, and D. Patrizio, **Thermodynamic Properties of Pure Hydrofluorocarbons by a Perturbed Hard-Sphere-Chain Equation of State**, *Chemical Engineering Science*, 52(9):1517-1527, May 1997 (11 pages, rdb8C26)

equation of state (EOS), thermodynamic properties, thermophysical data

P. S. Fialho (Universidade de Azores, Portugal) and C. A. Nieto de Castro (Universidade de Lisboa, Portugal), **Applications of the Hard Sphere DeSantis Equation of State to the Estimation of the Density of Compressed Alternative Refrigerants**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:187-192, 1995 (6 pages with 5 figures and 3 tables, RDB7804)

R-22, R-114, R-123, R-142b, R-152a, liquid density, Hard Sphere DeSantis (HSDS, DeSantis) equation of state (EOS), thermodynamic properties, thermophysical data

E. Fransson and L. Vamling (Chalmers University of Technology, Sweden), **The Abdoul-Rauzy-Peneloux Group Contribution Equation of State Extended to CFC-Containing Mixtures**, *Chemical Engineering Science,* 48(10):1753-1759, May 1993 (7 pages, rdb8946)

discusses use of the Abdoul-Raury-Peneloux (ARP) equation of state (EOS), which combines a group contribution excess Helmholtz energy model with traditional cubic EOSs, for prediction of refrigerant blends: this EOS, initially developed for petroleum mixtures, has been extended to cover compounds containing chlorine and fluorine, yielding a predictive method for the thermodynamic properties of mixtures; presents 19 general group parameters estimated from experimental data for 31 binary systems with an error not exceeding 5.1%; this result demonstrates the effectiveness of the method, since the traditional mixing rules would have demanded 31 specific interaction parameters for the same number of systems, without the possibility of extending their validity to other mixtures; the ARP EOS also was applied to a ternary blend and to an azeotropic blends, neither of which was included in the estimation procedure, to verify the prediction ability; the results were deviations for calculated pressures of 0.7 and 2.6%, respectively

D. G. Friend, R. D. McCarty, and V. Arp, **NIST Thermophysical Properties of Pure Fluids**, Standard Reference Database (SRD) 12 version 3.0, National Institute of Standards and Technology (NIST), Gaithersburg, MD, 1992 (software and documentation available from NIST, rdb7A17)

R-702 (hydrogen), R-702p (parahydrogen), R-704 (helium), and others, transport data

M. Fukushima, S. Ohotoshi, and T. Miki (Asahi Glass Company, Limited, Japan), **Thermodynamic Properties Measurements of HFC-32 and HFC-125**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:207-214, 1995 (8 pages with 10 tables, rdb7806)

R-32, R-125, thermophysical data: critical parameters (temperature, pressure, and density), vapor-liquid coexistence curve, vapor pressure, PVT properties

M. Fukushima, **Saturated Liquid Densities of HCFC-123, HFC-134a, CFC-11, and CFC-12**, *Nippon Reito Kyokai Ronbunshu* [Transactions of the JAR], Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 8(1):65-75, 1991 (11 pages in Japanese, rdb4B49)

R-11, R-12, R-123, R-134a, thermodynamic properties, thermophysical data

M. Fukushima, N. Watanabe, and T. Kamimura, **Measurements of the PVT Properties of HCFC-123 and HFC-134a**, *Nippon Reito Kyokai Ronbun*shu [Transactions of the JAR], Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 7(3):243-256, 1990 (14 pages in Japanese, rdb4B50)

thermodynamic properties of R-123 and R-134a, thermophysical data

M. Fukushima, N. Watanabe, and T. Kamimura, **Measurements of the Vapor-Liquid Coexistence Curves and the Critical Parameters of HCFC-123 and HFC-134a**, *Nippon Reito Kyokai Ronbunshu* [Transactions of the JAR], Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 7(2):85-89 (possibly 85-95), 1990 (5 pages in Japanese, rdb4B51)

thermodynamic properties of R-123 and R-134a, thermophysical data

C. L. Gage, **Equation-of-State Parameters for Potential CFC and HCFC Replacements**, Environmental Research Brief EPA-600/S-93-003, U.S. Environmental Protection Agency (EPA), Research Triangle Park, NC, February 1993 (2 pages with 2 tables, available from JMC as RDB3406)

This summary presents coefficients to calculate thermodynamic properties for 11 potential alternative refrigerants. These data are provided for use with for the Carnahan-Starling-DeSantis (CSD) equation of state (EOS). The summary also presents coefficients for a quadratic equation for the ideal gas heat capacity. The chemicals include nine hydrofluorocarbons (HFCs), namely R-227ca, R-227ea, R-236cb, R-236ea, R-236fa, R-245ca, R-245cb, R-245fa, and R-254cb. They also include two ethers, R-E125 and R-E143a.

V. Z. Geller, M. E. Paulaitis (University of Delaware), D. B. Bivens, and A. Yokozeki (DuPont Fluoroprod-

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ucts), **Transport Properties of Some Alternative Refrigerants**, *Energy Efficiency and Global Warming Impact* (proceedings of the meetings of Commissions B1 and B2, Ghent, Belgium 12-14 May 1993), International Institute of Refrigeration (IIR), Paris, France, 227-234, 1993 (8 pages with 1 figure and 2 tables, RDB4A47)

This paper presents tabular data for the thermal conductivity and viscosity of R-23 for -103 to 147 °C (-154 to 296 °F) and pressures of 100 kPa to 20 MPa (14.5-2900 psi). It also presents correlations for thermal conductivity and viscosity of R-22, R-23, R-32, R-134a, R-143a, and R-152a. These estimation methods cover dilute gases, saturated liquids and vapors, and liquids and vapors well removed from saturation conditions. The paper comments on the status of thermophysical and specifically transport property data. It notes that data for R-134a published in other studies differ by more than 20% and that estimates of viscosity by the most reliable methods may deviate from measured data by up to 50%. The paper summarizes the experimental methods used, which were based on a modified hot-wire apparatus for thermal conductivity and a modified capillary-tube method for viscosity measurements. A plot shows the correlation between reduced dilute gas velocity and reduced temperature for R-22, R-23, R-32, R-134a, R-143a, and R-152a, to substantiate that deviations in the new experimental data from a regression curve do not exceed 1.5%.

K. A. Gillis (National Institute of Standards and Technology, NIST), **Thermodynamic Properties of Seven Gaseous Halogenated Hydrocarbons from Acoustic Measurements: $CHClFCF_3$, CHF_2CF_3, CF_3CH_3, CHF_2CF_3, $CF_3CHFCHF_2$, $CF_3CH_2CF_3$, $CHF_2CF_2CH_2F$**, *International Journal of Thermophysics*, 18(7):73-135, January 1997 (63 pages with 18 figures and 18 tables, RDB8234)

measurements of the speed of sound using a cylindrical resonator for R-124, R-125, R-143a, R-152a, R-236ea, R-236fa, and R-245ca for differing temperature ranges between -33 and 127 °C (-28 and 260 °F) and pressures up to 1 MPa (145 psia): presents deduced ideal-gas heat capacities and coefficients for both acoustic and density virial equations; thermophysical data

K. A. Gillis and M. R. Moldover (National Institute of Standards and Technology, NIST), **Practical Determination of Gas Densities from the Speed of Sound Using Square-Well Potentials**, *International Journal of Thermophysics*, 17(6):1305-1324, 1996 (20 pages with 9 figures and 3 tables, errata for equation 10, RDB8911)

thermodynamic properties for R-50, R-125, and R-134a; relationships between the first three density virial coefficients and the first four acoustic virial coefficients; coefficients for hard-core square-well potential (HCSWP) determination of gas density and ideal-gas molar heat capacity; thermophysical data

K. A. Gillis (National Institute of Standards and Technology, NIST), **Thermodynamic Properties of Two Gaseous Halogenated Ethers from Speed of Sound Measurements: Difluoromethoxy-difluoromethane and 2-Difluoromethoxy-1,1,1-trifiuoroethane**, *International Journal of Thermophysics*, 15(5):821-847, 1994 (27 pages with 8 figures and 5 tables, RDB8254)

thermodynamic properties for R-E134 and R-E245fa1 for -48 to 111 °F (-55 to 232 °F): presents measurements of the speed of sound and derived ideal-gas heat capacities and second acoustic virial coefficients; thermophysical data

A. R. H. Goodwin, D. R. Defibaugh, and L. A. Weber (National Institute of Standards and Technology, NIST), **The Vapor Pressure of 1,1,1,2-Tetrafluoroethane (R134a) and Chlorodifluoromethane (R22)**, *International Journal of Thermophysics*, 13(5):837-854, September 1992 (18 pages with 6 figures and 1 table, available from JMC as RDB3712)

thermodynamic properties of R-22 and R-134a; thermophysical data

A. R. H. Goodwin and G. Morrison (National Institute of Standards and Technology, NIST), **Measurement of the Dipole Moment of Gaseous 1,1,1-Trichlorotrifluoroethane, 1,2-Difluoroethane, 1,1,2-Trichlorotrifluoroethane, and 2-(Difluoromethoxy)-1,1,1-trifluoroethane**, *Journal of Physical Chemistry*, 96:5521-5526, 25 June 1992 (6 pages with 4 figures and 3 tables, available from JMC as RDB3710)

R-113a, R-152, R-113, R-E245, thermophysical properties, data

A. R. H. Goodwin and M. R. Moldover (National Institute of Standards and Technology, NIST), **Thermophysical Properties of Gaseous Refrigerants from Speed of Sound Measurements: III. Results for 1,1-Dichloro-2,2,2-trifluoroethane ($CHCl_2$-CF_3) and 1,2-Dichloro-1,2,2-trifluoroethane (CHClF-$CClF_2$)**, *Journal of Chemical Physics*, 95(7):5236-5242, 1 October 1991 (7 pages with 4 figures and 4 tables, RDB3106)

R-123, R-123a, thermophysical properties, data

A. J. Grebenkov, V. P. Zhelezny, P. M. Klepatsky, O. V. Beljajeva, Y. A. Chernjak, Y. G. Kotelevsky, and B. D. Timofejev (Academy of Sciences, Minsk, Belarus), **Thermodynamic and Transport Properties of Some Alternative Ozone-Safe Refriger-**

ants for Industrial Refrigeration Equipment: Study in Belarus and Ukraine, *Preprints of the 12th Symposium on Thermophysical Properties* (Boulder, CO, 19-24 June 1994), American Society of Mechanical Engineers (ASME), New York, NY, June 1994; republished in *International Journal of Thermophysics*, 17(3):535-549, May 1996 (15 pages, rdb7649)

properties of R-32, R-125, R-134a, R-152a, and R-218 as well as some of their binary mixtures: phase equilibrium parameters (boiling and condensing curve, critical point, thermophysical properties at these parameters, and heat of evaporation); isobaric and isochoric heat capacity, enthalpy, and entropy in the gas and liquid state; speed of sound, thermal conductivity, viscosity, and density in the gas and liquid state; dielectric properties and surface tension; compatibility with materials inside the refrigerant circuit; and solubility in lubricants

J. J. Grebner and R. R. Crawford (University of Illinois at Urbana-Champaign), **Measurement of Pressure-Temperature-Concentration Relations for Mixtures of R12/Mineral Oil and R134a/Synthetic Oil**, paper 3660, *Transactions* (Winter Meeting, Chicago, IL, January 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(1):387-396, 1993 (10 pages with 9 figures and 6 tables, RDB-6C23)

properties of refrigerant-lubricant mixtures: R-12 with two mineral oils, one naphthenic and one paraffinic, at concentrations from 1-100% m/m R-12; R-134a with a polyalkylene glycol (PAG) and with a one polyolester (POE) synthetic lubricants at 5-100% m/m R-134a; empirical relations to predict the solubility behavior; comparisons to predictions based on Raoult's rule and Flory-Huggins theory; thermophysical data

J. J. Grebner and R. R. Crawford (University of Illinois at Urbana-Champaign), **The Effects of Lubricant on Evaporator Capacity for Systems Using Mixtures of R-12/Mineral Oil and R-134a/Synthetic Oil**, paper 3659, *Transactions* (Winter Meeting, Chicago, IL, January 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(1):380-386, 1993 (7 pages with 4 figures and 3 tables, RDB6C35)

properties of refrigerant-lubricant mixtures: R-12 with two mineral oils, one naphthenic and one paraffinic, at concentrations from 1-100% m/m R-12; R-134a with a polyalkylene glycol (PAG) and with a one polyolester (POE) synthetic lubricants at 5-100% m/m R-134a; empirical relations to predict the solubility behavior for -46 to 121 °C (-50 to 250 °F); comparison of measured evaporator performance to that predicted using calculated, theoretical enthalpies and pressure-temperature-concentration relations at lubricant concentrations of 1, 5, and 10% m/m; found that effects of oil solubility on evaporator capacity reduction were greater for R-12/mineral oil than for R-134a/synthetic oil

U. Groß and Y. W. Song (Universität Stuttgart, Germany), **Thermal Conductivities of the New Refrigerants R125 and R32 Measured by the Transient Hot-Wire Method**, *International Journal of Thermophysics*, 17:607-619, 1996 (13 pages, rdb-8914)

R-32 and R-125; thermodynamic properties, thermophysical data

U. Groß, Y. W. Song, and E. Hahne (Universität Stuttgart, Germany), **Thermal Conductivity of the New Refrigerants R134a, R152a, and R123 Measured by the Transient Hot-Wire Method**, *International Journal of Thermophysics*, 13:957-983, 1992 (27 pages, rdb4A46)

R-123, R-134a, R-152a, thermodynamic properties, thermophysical data

U. Groß, Y. W. Song, J. Kallweit, and E. Hahne (Universität Stuttgart, Germany), **Thermal Conductivity of Saturated R-123 and R-134a, Transient Hot Wire Measurements**, *Thermophysical Properties of Pure Substances and Mixtures for Refrigeration* (proceedings of the meeting of IIR Commission B1, Herzlia, Israel, March 1990), International Institute of Refrigeration (IIR), Paris, France, 103-108, 1990 (6 pages with 5 figures and 3 tables, RDB3921)

transport properties, thermophysical data

V. A. Gruzdev and A. I. Shumskaya, **Experimental Investigation of Isobaric Specific Heats of Vapors of Freons: F-11, F-12, F-13, F-21, F-22, and F-23**, *Teplofizicheskie Svoistva Veshchestv i Materialov* [Thermophysical Properties of Substances and Materials], Izdatel'stvo Standartov, Moscow, Russia, 8:108-129, 1975 (22 pages in Russian, rdb4A59)

R-11, R-12, R-13, R-21, R-22, R-23, thermodynamic properties, thermophysical data

J. Guilpart, D. Leducq, and R. Belance (Cemagref, France), **Computer Subroutines for Rapid Evaluation of Natural Refrigerants Thermodynamic Properties**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrig-

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oration (IIR), Paris, France, 449-457, 1998 (9 pages with 10 tables, RDB9248)

provides simplified equations for the vapor pressure, saturation temperature, liquid enthalpy, saturated vapor enthalpy, superheated vapor enthalpy, saturated vapor specific volume, superheated vapor specific volume, liquid specific volume, saturated vapor entropy, and superheated vapor entropy for R-290 (propane), R-600 (n-butane), R-600a (isobutane), R-717 (ammonia), R-718 (water), and R-744 (carbon dioxide); includes discussion by B. Adamson (Refrigeration Engineering Pty Limited, Australia), D. Colbourne (Calor Gas Limited, UK), and R. Camporese (Consiglio Nazionale della Ricerche, CNR, Italy)

B. V. Gunchuk, V. P. Zhelezny, I. A. Zhosul, L. Y. Lyasota, M. D. Potapov, and V. P. Eizenbeis, **Study of the Density, Viscosity, Thermal Conductivity, and Surface Tension of Coolants R116, R132B2, R318, and R329 as well as Azeotropic Mixtures of R23 + R116 and R116 + R13 at the Boiling Line**, *Teplofizicheskie Svoistva Veshchestv i Materialov* [Thermophysical Properties of Substances and Materials], Izdatel'stvo Standartov, Moscow, Russia, 28:99-118, 1989 (in Russian, rdb6813)

R-116, R-132B2, R-C318, R-329, R-23/116, R-13/116, thermodynamic and transport properties, thermophysical data

X. Guozhen, W. Yezheng, D. Kunxuan, and C. Zhong (Xi'an Jiaotong University, China), **The Relations Used to Analyze the Phase Equilibrium Properties of Binary Refrigerant Mixtures**, *Proceedings of the 1992 International Refrigeration Conference - Energy Efficiency and New Refrigerants*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 2:425-432, July 1992 (8 pages with 2 figures and 4 tables, RDB2825)

A. N. Gurova, C. A. Nieto de Castro, and U. V. Mardolcar (Universidade de Lisboa, Portugal), **The Thermal Conductivity of Liquid Halocarbons**, *Proceedings of the Fourth Asian Thermophysical Properties Conference* (Tokyo, Japan, 5-8 September 1995), 129-132, 1995 (4 pages, rdb8456)

transport properties of R-123 and others; thermophysical data

A. N. Gurova, T. G. Barao, C. A. Nieto de Castro, and U. V. Mardolcar (Universidade de Lisboa, Portugal), **The Thermal Conductivity and Dielectric Constant of HCFC-141b, HCFC-123, HCFC-142b, and HFC-134a**, *High Temperatures - High Pressures*, 26:25-34, 1994 (10 pages, rdb8457)

physical and transport properties of R-123, R-134a, R-141b, and R-142b; thermophysical data

U. Hammerschmidt, **Thermal Conductivity of a Wide Range of Alternative Refrigerants Measured with an Improved Guarded Hot Plate Apparatus**, *International Journal of Thermophysics*, 16:-1203-1212, 1995 (10 pages, rdb8462)

thermal conductivity of R-22, R-123, R-152a, and others; transport properties; thermophysical data

U. Hammerschmidt, **Die Wärmeleitfähigkeit von Monochlordifluormethan (R22), Dichlortrifluorethan (R123), und Difluorethan (R152a) im Temperaturbereich von 30 bis 190 °C bei Atmosphärendruck** [The Thermal Conductivity of Monochlorodifluoromethane (R-22), 2,2-Dichloro-1,1,1-trifluoroethane (R-123), and 1,1-Difluoroethane (R-152a) in the Temperature Range from 30 to 190 °C (86 to 374 °F) at Atmospheric Pressure], *PTB-Mitt,* 101:95-106, 1991 (12 pages in German, rdb8463)

thermal conductivity of R-22, R-123, and R-152a: transport properties, thermophysical data

G. Händel, R. Kleinrahm, and W. Wagner, **Measurements of the Pressure-Density-Temperature Relations of Dichlorodifluoromethane (R12) and Chlorodifluoromethane (R22) in Parts of the Homogeneous Gas and Liquid Regions on the Coexistence Curve**, *Journal of Chemical Thermodynamics*, 24:697-713, 1992 (17 pages, rdb8204)

thermodynamic properties of R-12 and R-22, thermophysical data

W. M. Haynes (National Institute of Standards and Technology, NIST), **Thermodynamic Properties of HCFC Alternatives**, report DOE/CE/23810-80, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, November 1996 (184 pages with 47 figures and 42 tables, available from JMC as RDB7401)

This report summarizes measurements with high accuracy of primary thermodynamic data for one ternary and nine binary as potential replacements (or binary constituents of potential replacements) for R-22 or R-502. They include R-32/125, R-32/125/134a, R-32/134a, R-32/143a, R-32/290, R-125/134a, R-125/143a, R-125/290, R-143a/-134a, and R-290/134a. Measurements also were made for R-41 and R-41/744 (a blend to reduce the flammability of neat R-41) as potential replacements for R-13. The report discusses the characteristics of each of the blends and measurements made of both vapor-liquid-equilibrium (VLE) and near-saturation properties. It characterizes each blend as one of two types, distinguished by having or not having liquid-liquid immiscibility, and notes the potential for azeotropes for them. The raw data are tabulated and plots compare them with values calculated using the Lemmon-Jacobsen (LJ) model, for which mixing parameters were determined from the data. The data for R-41 were fit to a modified Benedict-Webb-Rubin (MBWR) equation of state. The report compares the measured data to published findings from other studies and discusses the implementation of the LJ models in REFPROP 6.0. A table provides the derived interaction parameters for the LJ model. Two appendices present the experimental apparatus used and gas chromatograph calibration procedures. The apparatus include a calorimeter and instruments to measure dynamic phase equilibria, bubble point and near saturation properties, isochoric properties, and sound speed by a spherical resonator; each is shown schematically. Another appendix discusses the estimated uncertainties in state-points. All of the tables are repeated in metric (SI) and inch-pound (IP) units of measure.

W. M. Haynes (National Institute of Standards and Technology, NIST), **Thermophysical Properties of HFC-143a and HFC-152a**, report DOE/CE/23810-39, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, July 1994 (190 pages with including 27 figures and 47 tables, available from JMC as RDB4B09)

This report presents raw and smoothed data for the thermophysical properties of R-143a and R-152a. It also provides modified Benedict-Webb-Rubin (MBWR) equations of state and transport property models. The objective of the study was to fill gaps in current data and resolve problems and uncertainties that exist in and between such data. The report summarizes the measurement methods used and estimated precision. The apparatus included a Burnett apparatus for pressure-volume-temperature (PVT) relations; an isochoric apparatus for liquid density; an ebulliometer and Burnett apparatus for vapor pressure; an optical cell for refractive index, capillary rise, and indirectly the critical density; a cylindrical acoustic resonator for speed of sound; an adiabatic calorimeter for molar heat capacity; low- and high-temperature transient hot-wire instruments for thermal conductivity; a torsionally oscillating quartz crystal viscometer for shear viscosity; and a capillary viscometer for liquid viscosity. The ranges of measurements, representative data, and deviations from the MBWR equation and ancillary equations for vapor pressure and saturated liquid and vapor densities are plotted. An appendix presents the extensive measured data in a series of tables along with the equations of state (EOS), critical parameters, Ideal gas heat capacity equations, and derived thermodynamic properties for both R-143a and R-152a. Except for the equations and critical parameters, all of the data are provided in both metric (SI) and inch-pound (IP) units. Derived tables give the pressure, liquid density, vapor specific volume, specific heat ratio for the vapor, and liquid and vapor enthalpy, entropy, specific heat, and velocity of sound from the triple to the critical points at 10 °C and 20 °F Intervals. Equations and tabular data also are provided for thermal conductivity and viscosity. A second appendix describes a correlation technique used with the transient hot wire measurements.

N. J. Hewitt, J. T. McMullan, B. Mongey, and R. H. Evans (University of Ulster, UK), **Development of Engineering Design Data for New Refrigerants I: Pure Fluids and Azeotropic Mixtures**, *International Journal of Energy Research* (IJER), 20(1):143-155, January 1996 (13 pages with 9 figures and 11 tables, RDB9604)

presents critical properties and equations for the vapor pressure, ideal gas specific heat capacity, and liquid density as well as Martin-Hou (MH) equations of State (EOS) for R-32, R-124, R-125, R-134a, and R-143a; provides pressure-enthalpy (PH) charts created with these equations in inch-pound (IP) units of measure; presents similar data and equations derived for R-410A, R-507A, and R-32/125 (60/40) - a candidate R-410 series blend; thermodynamic properties; thermophysical data

Y. Higashi (Iwaki Meisel University, Japan), **Survey of the Critical Parameters for HFC Refrigerants**, report for IEA HPC Annex 18, International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, 1996 (rdb8973)

thermodynamic properties for R-32, R-125, and others; critical temperature, pressure, and density; thermophysical data

Y. Higashi (Iwaki Meisei University, Japan), **Vapour-Liquid Equilibrium, Coexistence Curve and Critical Locus for Binary R-32/125 Mixture,** *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:297-304, 1995 (8 pages with 8 figures and 3 tables, RDB7819)

R-32/125 (R-410 series) blends, thermodynamic data, thermophysical properties, interaction parameters for the Carnahan-Starling-DeSantis (CSD), Peng-Robinson (PR), and Redlich-Kwong-Soave (RKS) equations of state (EOS)

Y. Higashi (Iwaki Meisel University, Japan), **Critical Parameters for HFC-134a, HFC-32 and HFC-125,** *Energy Efficiency and Global Warming Impact* (proceedings of the meetings of Commissions B1 and B2, Ghent, Belgium 12-14 May 1993), International Institute of Refrigeration (IIR), Paris, France, 167-174, 1993; republished in *International Journal of*

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Refrigeration (IJR), 17:524-531, 1994 (8 pages with 5 figures and 2 tables, RDB5313)

R-32, R-125, R-134a

Y. Higashi (Iwaki Meisel University, Japan) and M. Okada (Tsukuba College of Technology, Japan), **Measurement of the Surface Tension for CFC Alternatives**, paper 83, *New Challenges in Refrigeration* (proceedings of the XVIllth International Congress of Refrigeration, Montreal, Québec, Canada, 10-17 August 1991), International Institute of Refrigeration, Paris, France, 11:675-679, August 1991 (5 pages with 12 figures and 2 tables, RDB-4B22)

R-123, R-134b, R-142b, R-152a, R-225ca, R-225cb, surface tension, transport properties, thermophysical data

C. D. Holcomb, V. G. Niesen, L. J. Van Poolen, and S. L. Outcalt (National Institute of Standards and Technology, NIST), **Coexisting Densities, Vapor Pressures, and Critical Densities of Refrigerants R-32 and R-152a at 300 to 385 K**, *Fluid Phase Equilibria,* 91:145-157, 1993 (13 pages with 8 figures and 3 tables, RDB4A44)

presents measurements of the vapor pressures and coexisting densities of R-32 and R-152a from 27 °C (80 °F) to near their respective critical point temperatures; also presents analyses of the density data to determine an internally consistent critical densities using the critical liquid volume fraction method; provides correlations of the measured data and compares them to findings from other studies; thermodynamic properties; thermophysical data

J. C. Holste, H. A. Duarte-Garza, and M. A. Villamanan-Olfos (Texas A&M University), **Thermodynamic Properties Measurements**, paper 93-WA/HT-60 (Winter Annual Meeting, New Orleans, LA, 28 November - 3 December 1993), American Society of Mechanical Engineers (ASME), New York, NY, 1993 (6 pages, rdb8933)

outlines experimental methods used to investigate the properties of alternative refrigerants; they include a continuously weighed pycnometer, an isochoric apparatus, a Burnett apparatus, and a visual cell for determining critical temperatures; presents results of measurements for R-125, R-134a, and R-141b along with compressed liquid densities for R-32

M. L. Huber (National Institute of Standards and Technology, NIST) and J. F. Ely (Colorado School of Mines), **Prediction of Viscosity of Refrigerants and Refrigerant Mixtures**, *Fluid Phase Equilibria,* 80(11):239-248, 1992 (10 pages with 4 figures and 2 tables, available from JMC as RDB3706)

transport properties; thermophysical data; extended corresponding states (ECS) model using a Benedict-Webb-Rubin (BWR) equation for R-134a, as a reference fluid; coefficients for R-11, R-12, R-13, R-22, R-23, R-113, R-114, R-115, R-123, R-141b, and R-152a

M. L. Huber (National Institute of Standards and Technology, NIST) and J. F. Ely (Colorado School of Mines), **Prediction of the Thermal Conductivity of Refrigerants and Refrigerant Mixtures**, *Fluid Phase Equilibria,* 80(11):249-261, 1992 (13 pages with 3 figures and 2 tables, available from JMC as RDB3707)

thermophysical data; extended corresponding states (ECS) model using a Benedict-Webb-Rubin (BWR) equation for R-134a, as a reference fluid

J. J. Hurly, J. W. Schmidt, S. J. Boyes, and M. R. Moldover (National Institute of Standards and Technology, NIST), **Virial Equation of State of Helium, Xenon, and Helium-Xenon Mixtures from Speed-of-Sound and Burnett P-ro-T Measurements**, *International Journal of Thermophysics,* 18(3):579-634, May 1997 (46 pages with 10 figures and 11 tables, RDB8912)

thermodynamic properties of R-704, R-7131, and R-704/7131 blends; equation of state (EOS) for 40-180 °C (104-356 °F) and 50-7,700 kPa (7-1,117 psia); measurements of the gas density with a Burnett apparatus and speed of sound by a cylindrical resonance apparatus; thermophysical data

M. Ibreighith, M. Fiebig, A. Lelpertz, and G. Wu, **Thermal Diffusivity of the Alternative Refrigerants R123, R134a, R142b, and R152a in the Liquid Phase**, *Fluid Phase Equilibria,* 80(11):323-332, 1992 (10 pages, rdb8460)

transport properties of R-123, R-134a, R-142b, and R-152a: thermophysical data

I. Iwata, C-C. Piao, and M. Noguchi (Daikin Industries, Limited, Japan), **HFC-32/125/134a - An Experimental Study of PVTx Properties of HCFC-22 Alternatives**, paper 95-252, *Proceedings of the 29th Japanese Joint Conference on Air Conditioning and Refrigeration* (Tokyo, Japan, 18-20 April 1995), 45-48, 1995 (4 pages with 3 figures and 2 tables, in Japanese, RDB7852)

presents an equation of state (EOS) for R-32/125 (R-410 series), R-32/134a, R-125/134a, and R-32/125/134a (R-407 series) blends based on 18-coefficient modified Benedict-Webb-Rubin (MBWR) equations for the components with new mixing rules; compares calculated properties to experimental data; thermophysical data

S. Kabelac (Universität Hannover, Germany), **Simple Set of Equations of State for Process Calculations and its Application to R134a and R152a**, *International Journal of Refrigeration,* 14(4):217-222, July 1991 (6 pages, rdb8974)

provides equations for consistent and reliable calculation of thermodynamic properties; separate equations calculate vapor pressure, gas phase pressure, volume and temperature (PVT) properties, saturated liquid densities, and the specific heat capacity in the ideal gas domain; the structure of these equations is simple because the critical region is excluded; few experimental data points are required for parameter regression, which makes the equations suitable for new refrigerants; presents derived relationships for enthalpy and entropy; gives examples for R134a and R152a

A. Kamei, C-C. Piao, H. Sato, and K. Watanabe (Keio University, Japan), **Thermodynamic Charts and Cycle Performance of** [H]**FC-134a and** [H]**FC-152a**, paper 3318, *Transactions* (Winter Meeting, Atlanta, GA, 10-14 February 1990) American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 96(1):141-149, 1990; republished in *CFC Alternatives,* technical data bulletin 6(1), ASHRAE, 10-18, June 1990 (9 pages with 13 figures and 5 tables, RDB3110)

thermodynamic properties and cycle performance for R-134a and R-152a

R. F. Kayser (National Institute of Standards and Technology, NIST), **Thermophysical Properties**, report DOE/CE/23810-16, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, April 1993 (242 pages, including 23 figures and 75 tables, available from JMC as RDB3860)

This report summarizes experimental measurements to provide highly accurate, thermophysical property data for R-32, R-123, R-124, and R-125. The report reviews the methods and apparatus used to complete data measurements, resolve problems and uncertainties that existed in prior data sets, fit equations of state (EOS), and develop transport property models for these fluids. Figures show the ranges of measured data, comparisons between the data and deviations from equation of state or regression values, and comparisons of the findings to results reported by other researchers. An appendix presents measured thermodynamic and transport data, in both metric (SI) and inch-pound (IP) units. The data addressed include measurements of Burnett vapor-phase pressure-volume-temperature (PVT) relations, vibrating-tube compressed liquid density, liquid PVT data, vapor pressures using both Burnett apparatus and an ebulliometer, saturated vapor and liquid densities, vapor pressure, liquid and two-phase heat capacity, viscosity, speed of sound, and derived ideal-gas heat capacity and acoustic virial coefficients. Coefficients are provided for modified Benedict-Webb-Rubin (MBWR) equations of state for the four refrigerants. A second appendix outlines a generalized correlation developed for thermal conductivity data. Conductivity data, measured with a transient hot-wire device, and correlation parameters are provided for R-32 and R-123.

J. Kilner and R. J. B. Craven, **Comparisons of Equations of State with Experimental Data for R-32 and R-125**, report HPP-AN18-4 for IEA HPC Annex 18, International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, 1997 (rdb8972)

thermodynamic properties for R-32 and R-125; equations of state (EOS); thermophysical data

D. S. Kim, J. Y. Kim, and S. T. Ro, **Thermal Conductivity of Alternative Refrigerants and their Mixtures in the Liquid State**, *Thermal Conductivity 22*, Technomic Publishing Company, Tempe, AZ, 177-188, 1994 (12 pages, rdb8455)

transport properties of R-123 and others; thermophysical data

Y. Kim, R. E. Sonntag, and C. Borgnakke (University of Michigan), **Generalized Equation of State for Refrigerants,** paper 3833, *Transactions* (Winter Meeting, Chicago, IL, 28 January - 1 February 1995), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(1):3-16, 1995 (14 pages with 12 figures and 13 tables, RDB5229)

thermodynamic properties of methane- and ethane-series refrigerants based on three reference fluids, namely R-152a, R-600 (butane), and R-740 (argon): presents a new four-parameter generalized equation of state (EOS) based on critical temperature, critical pressure, acentric factor, and polarity factor; provides an estimation method using the group contribution method for use when the four cited parameters are not available for refrigerants of interest; thermophysical data

Y. Kim and R. E. Sonntag (University of Michigan), **Estimation of Transport Properties of Refrigerants,** paper 94-WA/HT-7 (Winter Annual Meeting, Chicago, IL, 6-11 November 1994) , American Society of Mechanical Engineers (ASME), New York, NY, 1994 (rdb8907)

transport properties, thermophysical data

S. B. Kiselev and J. C. Rainwater, **Extended Law of Corresponding States and Thermodynamic**

Properties of Binary Mixtures In and Beyond the Critical Region, *Fluid Phase Equilibria,* 141(1-2):129-154, December 1997 (26 pages, rdb8C32)

thermodynamic properties of hydrocarbons, R-717 (ammonia), R-718 (water), R-744 (carbon dioxide); vapor-liquid equilibria (VLE); thermophysical data

M. Kleemiß and H. D. Baehr (Universität Hannover, Germany), **Experimental Results for the VLE of the Ternary Mixtures HFC 134a HFC 125/HFC 32 and HFC 134a/HFC 143a/HFC 125**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (1111), Paris, France, IVa:345-352, 1995 (8 pages with 9 figures, rdb7823)

vapor-liquid equilibrium (VLE) predictions for R-32/125/134a (R-407 series) and R-125/143a/-134a (R-404 series): measurements of the equimolar binary mixture interaction coefficients for R-32/125, R-32/134x, R-125/134x, R-125/143x, and R-143a/134a; thermodynamic properties, thermophysical data

M. Kleemiß, thesis, Universität Hannover, Hannover, Germany, 1994 (rdb8969)

thermodynamic properties of R-32/134a; thermophysical data

M. Kleiber (Technische Universität Braunschweig, Germany), **Vapor-Liquid Equilibria of Binary Refrigerant Mixtures Containing Propylene or R134a**, *Fluid Phase Equilibria,* 92:149-194, 15 January 1994 (46 pages, rdb8934)

presents experimental vapor-liquid equilibria data for R-12/134a, R-13/1270, R-13B1/1270, R-23/-1270, R-116/134a, R-116/1270, R-134a/142b, R134a/152a, R-290/134a, R-1270/12, R-1270/22, R-1270/114, R-1270/115, R-1270/134a, R-1270/-142b, and R-1270/152a obtained at temperatures between -22 to 25 °C (-8 to 77 °F) and pressures up to 2 MPa (2900 psia); shows the consistency of the data by a maximum-likelihood method; correlates the data by various forms of generalized equations of state (EOSs); comments on addition of the CClF- group to the UNIFAC parameter matrix

S. A. Klein (University of Wisconsin), M. O. McLinden, and A. Laesecke (National Institute of Standards and Technology, NIST), **An Improved Extended Corresponding States Method for Estimation of Viscosity of Pure Refrigerants and Mixtures**, *International Journal of Refrigeration* (IJR), 20(3):208-217, May 1997 (10 pages with 6 figures and 2 tables, available from JMC as RDB7946)

extended corresponding states (ECS) method using R-134a as the reference fluid to calculate the viscosity of refrigerants; data and deviations for R-11, R-12, R-22, R-32, R-113, R-123, R-125, R-143a, R-152a, R-290 (propane), R-600 (n-butane), and R-600a (isobutane); modifications for mixtures; comparisons to published data for R-32/134a (25/75) and (33/67), R-32/125/134a (30/20/60), R-125/134a (53/47), R-402A, R-402B, and R-404A

F. Kohler and N. Van Nhu, **The Second Virial Coefficients of Some Halogenated Ethanes**, *Mol. Phys*., 80:795-800, 1993 (6 pages, rdb8259)

thermodynamic properties of R-143a and others; thermophysical data

R. Köster, **Thermodynamic Properties of Binary and Ternary Mixtures of the Refrigerants, R32, R125, R134a, and R143a**, *Fuel And Energy Abstracts*, 38(5):347, September 1997 (1 page, rdb-8C30)

thermodynamic properties of R-32, R-125, R-134a, R-143a, and blends of them; thermophysical data

K. Kraft, S. Will, and A. Leipertz (Universität Erlangen-Nürnberg, Germany), **Spectroscopic Determination of Selected Thermophysical Properties of Transparent Fluids**, *Measurement,* 14(2):135-145, December 1994 (11 pages, rdb8922)

describes a method to determine the thermal diffusivity, sound velocity, and dynamic viscosity of refrigerants: presents experimental results for the thermal diffusivity and sound velocity of saturated R-142b from 5 °C (41 °F) to the critical point and for the dynamic viscosity of R-123 at 100 kPa (14.5 psia) for 15-24 °C (59-75 °F); The method involves a time-resolved analysis of the laser light scattered from hydrodynamic modes in a transparent sample or from seed particles dispersed in it

R. Krauss and K. Stephan (Universität Stuttgart, Germany), **Literature Survey on Thermophysical Properties of Natural Refrigerants**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 441-448, 1998 (8 pages with 1 figures and 2 tables and 25 references, RDB-9247)

tabulates characteristic data (formula, Chemical Abstracts Service registry number, molecular mass, normal boiling point, critical point temperature, and critical point pressure for R-170 (ethane), R-C270 (cyclopropane), R-290 (propane), R-C4-10 - (cyclopentane), R-600 (n-butane), R-600a (isobutane), R-717 (ammonia), R-

729 (air), R-744 (carbon dioxide), and R-1270 (propene); recommends "reliable" formulations for an equation of state (EOS), viscosity, and thermal conductivity for R-170, R-290, R-600, R-600a, R-717, R-717/718 (ammonia/water), R-718 (water), R-729, and R-744; describes and illustrates the MIDAS database on thermophysical and environmental properties of alternative refrigerants; includes discussion by Å. Melinder (Kungliga Tekniska Högskolan, KTH, Sweden) and J. Guilpart (Cemagref, France)

R. Krauss and K. Stephan (Universität Stuttgart, Germany), **Literaturübersicht über thermophysikalische Eigenschaften natürlicher Kältemittel** [Literature Survey on Thermophysical Properties of Natural Refrigerants], *Bericht über die Kälte-Klima-Tagung* [Proceedings of the Refrigeration and Air-Conditioning Conference] (Würzburg, Germany, 1998), Deutscher Kälte- and Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, 207-216, 1998 (10 pages, in German, rdb9914)

thermodynamic and transport properties; thermophysical data

R. Krauss and K. Stephan (Universität Stuttgart, Germany), **Literature Survey on Thermophysical Properties of Refrigerants**, *Proceedings of the 13th Symposium on Thermophysical Properties* (Boulder, CO, 22-27 June 1997), 1997; republished in the *International Journal of Thermophysics,* 19(6):1615-1621, 1998 (7 pages, rdb9906)

thermodynamic and transport properties; thermophysical data

B. Kruppa and J. Straub (Technische Universität München, TUM, Germany), **Measurement of Thermal Diffusivity of the Refrigerants R22 and R134a by Means of Dynamic Light Scattering**, *Preprints of the 11th Symposium on Thermophysical Properties* (Boulder, CO, 23-27 June 1991), American Society of Mechanical Engineers (ASME), New York, NY, 1991; republished in *Fluid Phase Equilibria,* 80(4):305-321, 30 November 1992 (17 pages, rdb8962)

presents 300 measurements of thermal diffusivity each for R-22 and R-134a by dynamic light scattering; measurements were carried out along the critical isochore, both coexisting phases, and up to seven isotherms within a range of state for reduced pressure of 0.5-3.0 and reduced densities of 0.2-2.3; provides an equation of state (EOS) determine isobaric heat capacity

A. Kumagai and S. Takahashi, **Saturated Liquid Viscosities and Densities of Environmentally Acceptable Hydrochlorofluorocarbons (HCFCs)**, *International Journal of Thermophysics,* 14(2):339-342, 1993 (4 pages, rdb7835)

transport properties, thermophysical data

A. Kumagai and S. Takahashi, **Viscosity of Saturated Liquid Fluorocarbon Refrigerants from 273 to 353 K**, *International Journal of Thermophysics,* 12(1):105-117, 1991 (13 pages, rdb5485)

R-152a and others for 0-80 °C (32-176 °F), transport properties, thermophysical data

S. Kuwabara, H. Sato, and K. Watanabe (Keio University, Japan), **Measurements of the Vapour-Liquid Coexistence Curve in the Critical Region and of the Critical Parameters for Several Alternative Refrigerants**, *Proceedings of the 13th European Conference on Thermophysical Properties* (Lisbon, Portugal, 1993), 1993; republished in *High Temperatures - High Pressures*, 26(1):35-40, 1994 (6 pages, rdb8926)

presents measurements of the critical temperatures and densities R-32, R-123, R-125, R-134, R-134a, R-142b, and R-152a: The critical point determined by visual observation of the disappearance of the meniscus at the vapor-liquid coexistence for the seven alternative refrigerants; the data for R-32 and R-125 are new; those for R-123, R-134, R-134a, R-142b, and R-152a are reassessed values converted from the IPTS-68 into the ITS-90 temperature scale; presents a nondimensional correlation for the vapor-liquid coexistence curve of each of the cited refrigerants

S. D. Labinov (Thermodynamic Center, Ukraine) and J. R. Sand (Oak Ridge National Laboratory, ORNL, USA), **An Analytical Method of Predicting Lee-Kesler-Plöcker Equation of State Binary Interaction Coefficients**, *International Journal of Thermophysics,* 16(6):1393-1411, November 1995 (18 pages with 10 figures and 4 tables, RDB5C01)

This paper presents a method to calculate binary interaction coefficient (IC) values for hydrocarbon mixtures for the Lee-Kesler-Plöcker (LKP) equation of state (EOS). The method is based on solving simultaneous equations from Plöcker's mixing rules, for pseudocritical parameters of a mixture, and the Lee-Kesler equation for the saturation line. This approach allows determination of binary ICs for both polar and nonpolar substances, with a maximum deviation of 0.4%. The calculations require the critical parameters of the components and their normal boiling temperatures, but no experimental data for the mixtures. A table summarizes the interaction coefficients published in other studies for R-22/114, R-22/142b, and R-22/152a for the LKP equation of state. A second table compares experimental and calculated coefficients

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for R-170 (ethane) mixed with R-290 (propane), R-600 (n-butane), n-pentane, n-hexane, n-heptane, n-octane, and n-nonane. A figure compares calculated and experimental values of these coefficients. A second figure compares the experimental and calculated compressibility factors against the acentric factor for methane through n-decane (alkanes with 1-10 carbon atoms). A third figure compares reduced properties (normalized to critical parameters) for boiling temperature for the pure substances and mixtures of ethane with nonane and ethane with propane. The paper also presents a method to determine ICs for mixtures of polar substances such as the homologs of methane and ethane, which include the primary alternative refrigerants and blend components. The basic physical properties (molecular mass, normal boiling and critical point temperatures, critical pressure, critical molar volume, and dipole moments) needed are tabulated along with basic data for 12 mixtures. They include R-22/114, R-22/124, R-22/142b, R-22/152a, R-23/114, R-23/134a, R-23/22, R-32/134a, R-134a/124b, R-134a/134, R-152a/124, and R-152a/134. Calculated and experimental LKP ICs are plotted for these mixtures to show the inadequacies of the algorithm without consideration of polarity. A similar plot compares the calculated ICs, obtained by including parameters indicative of polarity based on component data, to measurements. The paper concludes with an equation that approximates this approach, and yields errors of less than 5%. The results allow thermodynamic property calculations for mixtures of polar substances with a minimum of experimental property information, which can be estimated from the chemical structures of the components when necessary.

A. Laesecke and R. F. Hafer (National Institute of Standards and Technology, NIST), **Viscosity of Fluorinated Propane Isomers. 2. Measurements of Three Compounds and Model Comparisons**, *Journal of Chemical and Engineering Data,* 43(1):-84-92, 1998 (9 pages with 5 figures and 3 tables, RDB8227)

transport properties of R-227ea, R-245ca, and R-245fa for -25 to 75 °C (-13 to 167 °F): comparisons to extended-corresponding states (ECS) predictions; thermophysical data

A. Laesecke and D. R. Defibaugh (National Institute of Standards and Technology, NIST), **Viscosity of 1,1,1,2,3,3-Hexafluoropropane and 1,1,1,3,3,3-Hexafluoropropane at Saturated Liquid Conditions from 262 K to 353 K**, *Journal of Chemical and Engineering Data,* 41(1):59-62, 1996 (4 pages with 4 figures and 2 tables, RDB8228)

reports viscosity data for R-236ea and R-236fa; measurements were made in a capillary viscometer at -11 to 80 °C (12 to 176 °F) with an estimated uncertainty of ±3%; presents correlations to the Batschinski free-volume model and comparisons to predictions from an extended corresponding states (ECS) model; transport properties; thermophysical data

G. Latini, G. Passerini, F. Polonara, and G. Vitali (Università degli Studi di Ancona, Italy), **Alternative Refrigerants in the Liquid Phase: Thermal Conductivity of Binary and Ternary Mixtures**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 423-428, July 1996 (6 pages with 4 figures and 5 tables, RDB6C18)

prediction methods for thermal conductivity for refrigerant blends in their saturated liquid states and in the subcooled regions; methods using mixing rules and treatment of azeotropic mixtures as single compounds; thermodynamic properties; thermophysical data; citations of data sources for validation of R-22/134a, R-22/142b, R-22/152a, R-32/125, R-32/134a, R-123/141b, R-402A, R-402B, R-404A, and R-407D; deviations between experimental and predicted data

G. Latini, P. Passerini, and F. Polonara (Università degli Studi di Ancona, Italy), **Dynamic Viscosity of Alternative Refrigerants Along the Saturation Line**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:375-382, 1995 (8 pages with 2 figures and 5 tables, rdb7827)

correlation based on physical properties to estimate the liquid dynamic viscosity of refrigerants in the methane an ethane (C1-C2) series: R-10, R-11, R-12, R-13, R-13B1, R-20, R-21, R-22, R-23, R-30, R-32, R-40, R-114, R-115, R-123, R-123a, R-124, R-125, R-133a, R-134a, R-141b, R-142b, R-143a, R-152a, and R-160, transport properties, thermophysical data

G. Latini and F. Polonara (Università degli Studi di Ancona, Italy), **Dynamic Viscosity and Thermal Conductivity Prediction of Environmentally Safe Refrigerants,** *Non-CO_2 Greenhouse Gases,* edited by J. van Ham et al., Kluwer Academic Publishers, Dordrecht, The Netherlands, and Norwell, MA, USA, 357-362, 1994 (6 pages, rdb7830)

correlation to estimate transport properties, thermophysical data

G. Latini, P. Pierpaoli, and F. Polonara (Università degli Studi di Ancona, Italy), **Dynamic Viscosity and Thermal Conductivity Prediction of Refrig-**

erants and Refrigerant Mixtures, *Proceedings of the 1992 International Refrigeration Conference - Energy Efficiency and New Refrigerants*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 2:489-498, July 1992 (9 pages with 7 tables, RDB2832)

transport properties, thermophysical data

G. Latini, L. Laurenti, F. Marcotullio, and P. Pierpaoli (Università degli Studi di Ancona, Italy), **A General Prediction Method with Application to Refrigerants and Refrigerant Mixtures**, *International Journal of Refrigeration* (IJR), 13(6):248-255, July 1990 (8 pages, rdb7829)

correlation to estimate thermophysical data

S. Laugier, D. Richon, and H. Renon (ENSCPB-IAGP, France), **Bubble Pressures and Saturated Liquid Molar Volumes of Binary and Ternary Mixtures of Chlorofluorocarbons and Hydrochlorofluorocarbons**, *Fluid Phase Equilibria,* 93:297-316, 11 February 1994 (20 pages, rdb8929)

presents bubble pressures and saturated liquid molar volumes at several temperatures for R-23/22, R-23/114, R-23/114/113, and R-142b/113: the measurements were made using a variable volume cell and static isothermal equilibrium method; data were modeled with several cubic equations of state; concludes that either the regular or the generalized Trebble-Bishnoi-Salim (TBS) equation of state (EOS) yields the best representation

M-J. Lee and H-C. Sun (National Taiwan Institute of Technology, NTUT, Taiwan), **Thermodynamic Property Predictions for Refrigerant Mixtures**, *Industrial and Engineering Chemistry Research,* 31(4):1212-1216, April 1992 (5 pages, rdb8965)

presents correlations of vapor-liquid equilibrium (VLE) data of refrigerant blends by Soave, Patel-Teja, and Iwai-Margerum-Lu equations of state (EOSs) with one adjustable binary interaction constant, ka12; indicates that the Patel-Teja equation is slightly better than others; introduces a generalized equation for ka12 is that enables the Patel-Teja equation to predict the VLE properties for mixtures; predicts the bubble and dew point pressures for 55 binary blends containing R-22, R-32, R-123, R-124, R-125, R-134a, R-142b, R-143a, R-152a, R-1243, and R-E170 (dimethyl ether) at -40 to 90 °C (-40 to 194 °F) over their entire composition ranges; the predictions show that the near-azeotropic blends R-124/142b and R-134a/E170 are promising

E. W. Lemmon, **A Generalized Model for the Prediction of the Thermodynamic Properties of Mixtures Including Vapor-Liquid Equilibrium,** PhD thesis, University of Idaho, Moscow, ID, 1996 (rdb-7602)

equation of state (EOS) for refrigerant blends based on a Helmholtz free-energy model for mixtures (HMX) of hydrocarbons and simple inorganic compounds: employs binary interaction parameters and a generalized mixture function based on experimental data for 28 pairs of components: R-32/125, R-32/134a, R-125/134a, R134a/152a, R-50/170 (methane/ethane), R-50/290 (methane/propane), R-50/600 (methane/n-butane), R-50/600a (methane/isobutane), R-50/728 methane/nitrogen, R-50/744 (methane/-carbon dioxide), R-50/1150 (methane/ethene), R-170/290, R-170/600, R-170/744, R-290/600, R-290/600a, R-600a/600, R-720/744 (neon/-carbon dioxide), R-728/170, R-728/290, R-728/-600, R-728/732 (nitrogen/oxygen), R-728/740, R-728/744, R-740/50 (argon/methane), R-740/-732, R-740/744, and R-744/290; this model differs from the more general Lemmon-Jacobsen (LJ) model by addition of two terms specific to R-32/125

E. W. Lemmon, R. T. Jacobsen, S. G. Penoncello (University of Idaho), and S. W. Beyerlein, **Computer Programs for the Calculation of Thermodynamic Properties of Cryogens and Other Fluids**, *Advances in Cryogenic Engineering*, 39:1891-1897, 1994 (7 pages, rdb7A15)

R-702 (hydrogen), R-702p (parahydrogen), R-704 (helium), R-720 (neon), R-728 (nitrogen), R-729 (air), R-732 (oxygen), R-740 (oxygen), R-1150 (ethylene), R-1270 (propylene), and others: ALLPROPS properties model, thermodynamic properties, thermophysical data

D. Liangui, W. Wenchuan, Z. Danxing, and F. Jufu (Beijing University of Chemical Technology, China), **Optimization of the Compositions for CFC Alternative Mixture Refrigerants**, *Chinese Journal of Chemical Engineering,* 3(1):32-38, March 1995 (7 pages, rdb8920)

compares eight cubic equations of state (EOSs) for calculation of thermodynamic properties, for 26 chlorofluorocarbons (CFCs) and alternatives; recommends the modified Du-Guo EOS for accuracy; presents a method to develop optimized blend compositions as CFC alternatives by minimizing deviations between the vapor pressures of CFCs and alternative mixtures of interest; demonstrates the approach for R-22/142b, R-22/R152a, and R-22/152a/142b as replacements for R-12; deviations for the heat of vaporization are within 10 percent; concludes that the three blends examined behave as near-azeotropes and show promise as R-12 replacements based on thermodynamic properties alone

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M. Lisal and V. Vacek (Academy of Sciences, Czechoslovakia), **Effective Potentials for Liquid Simulation of the Alternative Refrigerants HFC-32 (CH_2F_2) and HFC-23 (CHF_3)**, *Fluid Phase Equilibria,* 118(1):61-76, 15 April 1996 (16 pages, rdb6B06)

site-site potentials for use in liquid simulations of R-23 and R-32 are constructed using effective interactions; these rigid molecules have interaction centers at the atomic sites coinciding with gas-phase monomer geometries; atomic interactions consist of van der Waals and Coulombic parts; the potential functions are adjusted to give simulated liquid properties for reduced temperatures (T/T_c) of 0.5-0.9 on the saturated liquid curves; proposed potentials are used in constant pressure and constant temperature and in constant temperature molecular dynamics simulations of the saturated liquids; the results are compared with experimental data

T. O. Lüddecke and J. W. Magee (National Institute of Standards and Technology, NIST), **Molar Heat Capacity at Constant Volume of Difluoromethane (R32) and Pentafluoroethane (R125) from the Triple-Point Temperature to 345 K at Pressures to 35 MPa**, *International Journal of Thermophysics,* 17(4):823-849, July 1996 (27 pages with 9 figures and 7 tables, RDB6B07)

measurements of the molar heat capacities at constant volume (Cv) of R-32 and R-125 with an adiabatic calorimeter; temperatures ranged from their triple points to 72 °C (161 °F) and pressures up to 35 MPa (5,100 psia); measurements were conducted on the liquid in equilibrium with its vapor and on compressed liquid samples; calorimetric results were obtained for two-phase saturated liquid and single-phase gas and liquid; these data were used to estimate vapor pressures for values less than 0.3 MPa (44 psia) by applying a thermodynamic relationship between the saturated liquid heat capacity and the temperature derivatives of the vapor pressure; the triple-point temperature and the enthalpy of fusion also were measured for each substance; principal sources of uncertainty are the temperature rise measurement and the change-of-volume work adjustment

Y. Maezawa, H. Sato, and K. Watanabe (Keio University, Japan), **Liquid Densities and Vapor Pressures of 1,1,2,2-Tetrafluoroethane (HFC-134) and 1,1-Dichloro-1-fluoroethane (HCFC-141b)**, *Journal of Chemical and Engineering Data,* 36:151-155, 1991 (5 pages, rdb4B53)

thermodynamic properties of R-134 and R-141b; thermophysical data

Y. Maezawa, H. Sato, and K. Watanabe (Keio University, Japan), **Saturated Liquid Densities of HCFC-123 and HFC-134a**, *Journal of Chemical and Engineering Data,* 35(3):225-228, 1990 (4 pages, rdb4310)

thermodynamic properties of R-123 and R-134a; thermophysical data

J. M. Martell and R. J. Boyd, **An Ab Initio Study of the Series of Fluorinated Ethanes C2Hn-F6-n (n=0-6): Geometries, Total Energies, and Carbon-Carbon Bond Dissociation Energies**, *Journal of Physical Chemistry,* 96(15):6287-6290, 1992 (4 pages, rdb5970)

R-116, R-125, R-134, R-134a, R-143a, R-152a, R-170, and others

V. Marx, A. Pruß, and W. Wagner, **Neue Zustandsgleichungen für R12, R22, R11 and R113. Beschreibung des thermodynamischen Zustandsverhaltens bei Temperaturen bis 525 K und Drücken bis 200 MPa** [New Equations of State for R-12, R-22, R-11, and R-113. Description of the Thermodynamic Property Data for Temperatures up to 252 °C (486 °F) and Pressures up to 200 MPa (29 psia)], report series 19 number 57, Verein Deutscher Ingenieure (VDI) [Association of German Engineers] Verlag, Düsseldorf, Germany, 1992 (in German, rdb5493)

thermodynamic properties of R-11, R-12, R-22, R-113; thermophysical data

T. Masukawa and M. Uematsu, **Formulation of the Generalized Correlations for the Thermodynamic Properties at the Saturated State for Component Substances Contained In the Natural Gases**, *Nippon Kikai Gakkai Ronbunshu* (Transactions of the Japan Society of Mechanical Engineers, JSME), JSME, Tokyo, Japan, B57(541):3176-3183, September 1991 (8 pages in Japanese, rdb8C34)

presents generalized correlations for the saturated vapor pressure, liquid and vapor densities, and heat of vaporization formulated on the three-parameter principle of corresponding states with acentric factor for 12 gases: they include R-50 (methane), R-170 (ethane), R-290 (propane), R-600 (n-butane), R-600a (isobutane), R-728 (nitrogen), R-732 (oxygen), R-734 (hydrogen sulfide), R-740 (argon), R-744 (carbon dioxide), R-784 (krypton), and R-7131 (krypton); the generalized correlations for the vapor pressure predicts the experimental data within ±1.0% for reduced temperatures (temperature divided by the critical temperature) greater than 0.4; the generalized correlation for the saturated liquid density predicts the experimental data within ±1.0% for temperatures from the triple point to the critical point; the generalized correlation for the saturated vapor density predicts the experimental data within ±2.0% for reduced temperatures greater than 0.5; the Clapeyron equation estimates the heat of vaporization within ±2.0% for reduced temperatures greater than 0.5 using the vapor pressure, saturated liquid density, and saturated vapor density from the proposed correlations; the reliability of the correlations was confirmed by comparison with experimental data for R-22 and R-114

S. Matsuo, Y. Tanaka, H. Kubota, and T. Makita, **Liquid Densities of HCFC-225ca, HCFC-225cb, and HCFC-141b**, *Journal of Chemical and Engineering Data,* 39:903 ff, 1994 (rdb8242)

thermodynamic properties of R-225ca, R-225cb, and R-141b; thermophysical data

R. D. McCarty, **Mathematical Models for the Prediction of Natural Gas Densities**, *Journal of Chemical Thermodynamics,* 14:837-854, 1982 (17 pages, rdb7A61)

R-50 (methane), R-170 (ethane), R-290 (propane), R-600 (n-butane), R-600a (isobutane), and others: hydrocarbon blends, LNG, thermophysical data

M. O. McLinden (NIST), S. A. Klein (University of Wisconsin), E. W. Lemmon (NIST), and A. P. Peskin (NIST), **Thermodynamic and Transport Properties of Refrigerants and Refrigerant Mixtures Database (REFPROP),** version 6 beta, National Institute of Standards and Technology (NIST), Boulder, CO, 1998 (RDB8814)

developmental extension of REFPROP version 6; see RDB8401 for production version

M. O. McLinden (National Institute of Standards and Technology, NIST), **Development of the REFPROP Database and Transport Properties of Refrigerants**, report DOE/CE/23810-97, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, July 1998 (42 pages with 7 figures and 6 tables, available from JMC as RDB8801)

This report outlines development of version 6.0 of the NIST Thermodynamic and Transport Properties of Refrigerants and Refrigerant Mixtures Database (REFPROP). It Identifies the three equations of state (EOS) used, which include a Modified Benedict-Webb-Rubin (MBWR), a Helmholtz energy, and an Extended-Corresponding-States (ECS) models. It describes use of the Lemmon-Jacobsen model for mixtures, mixing parameters determined from fits to experimental data, a predictive approach for mixtures lacking measured data, and 29 predefined mixtures. The report also presents fluid-specific correlations and an extended corresponding states model, used to represent the transport properties of refrigerants. It then describes a suite of FORTRAN subroutines and calling programs integrated into a main program with a graphical user Interface for the Windows® operating system. The single-compound (identified as "pure") refrigerants include R-11, R-12, R-13, R-14, R-22, R-23, R-32, R-41, R-113, R-114, R-115, R-116, R-123, R-124, R-125, R-134a, R-141b, R-142b, R-143a, R-152a, R-170, R-227ea, R-236ea, R-236fa, R-245ca, R-245fa, R-290 (propane), R-C318, R-600 (n-butane), R-600a (isobutane), R-717 (ammonia), R-744 (carbon dioxide), and R-1270 (propylene) [the report also cites R-134, but it is not included in REFPROP 6.0]. An appendix outlines the objectives of this REFPROP revision. A second appendix, prepared by E. W. Lemmon, presents the predictive model used for refrigerant mixtures. It applies mixing rules to the Helmholtz free energy of each of the mixture components. A table compares experimental fits to predicted mixing parameters for 75 binary pairs. A third appendix, co-authored by M. O. McLinden and S. A. Klein, presents an ECS model for the thermal conductivity of refrigerants, which modifies an earlier model. The enhancements introduce a shape factor, derived from experimental data, and an empirical correction. [Windows is a registered trademark of Microsoft Corporation]

M. O. McLinden (National Institute of Standards and Technology, NIST), S. A. Klein (University of Wisconsin), E. W. Lemmon (NIST), and A. P. Peskin (NIST), **Thermodynamic and Transport Properties of Refrigerants and Refrigerant Mixtures Database (REFPROP),** Standard Reference Database (SRD) 23 version 6.0, NIST, Gaithersburg, MD, 1998; correction issued as version 6.01 in July 1998 (software and documentation available from NIST at srdata@nist.gov for $200.00 or $100.00 to upgrade from previous versions; ARI members should contact kamrane@ari.org for availability; RDB8401)

Version 6.0 of REFPROP calculates properties for single-compound refrigerants as well mixtures of up to five of them. The refrigerants include R-11, R-12, R-13, R-14, R-22, R-23, R-32, R-41, R-113, R-114, R-115, R-116, R-123, R-124, R-125, R-134a, R-141b, R-142b, R-143a, R-152a, R-170, R-227ea, R-236ea, R-236fa, R-245ca, R-245fa, R-290 (propane), R-C318, R-600 (n-butane), R-600a (isobutane), R-717 (ammonia), R-744 (carbon dioxide), and R-1270 (propylene). REFPROP implements different equations of state (EOS) selected by fluid to provide the most accurate thermodynamic properties, including Modified Benedict-Webb-Rubin (MBWR), Helmholtz energy, and Bender equations as well as an Extended-Corresponding-States (ECS) model for fluids with limited data. Mixture calculations employ a new model,

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which applies mixing rules to the Helmholtz energy of the mixture components based on departure from ideal mixing. Viscosity and thermal conductivity are modeled with either fluid-specific correlations or a new ECS method. Properties can be calculated in user-selected units of measurement; they include temperature, pressure, density, specific volume, internal energy, enthalpy, entropy, speed of sound, specific heats at constant volume and pressure, compressibility, quality, composition, fugacity, viscosity, thermal conductivity, and surface tension. Data tables and plots (the latter as bitmaps) can be copied into other applications for subsequent analyses or use. REFPROP also provides information on single-compound refrigerants, including the ASHRAE Standard 34 designation (R number), chemical name, Chemical Abstract Service registry number, molar mass, triple-point temperature, normal boiling point (NBP) temperature, critical parameters (temperature, pressure, and density), acentric factor, and dipole moment at the NBP. It also indicates the range of applicability and provides literature references for the EOS and for the viscosity, thermal conductivity, and surface tension data used. This update replaces version 5.0 (see RDB6C15).

M. O. McLinden (National Institute of Standards and Technology, NIST), E. W. Lemmon (NIST), and R. T. Jacobsen (University of Idaho), **Thermodynamic Properties for the Alternative Refrigerants,** *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 135-154, 1997; republished in the *International Journal of Refrigeration* (IJR), 21(4):322-338, June 1998 (20 pages with 4 tables, RDB7B16)

summary of models to calculate the thermodynamic properties of refrigerants: addresses virial, cubic, Martin-Hou (MH), Benedict-Webb-Rubin (BWR), and Helmholtz energy equations of state (EOS) as well as an extended corresponding states (ECS) model; recommends high-accuracy formulations for 16 refrigerants including R-11, R-12, R-22, R-32, R-113, R-123, R-124, R-125, R-134a, R-143a, R-152a, R-290, R-600, R-600a, R-717, and R-744; discusses extension of these models for blends through use of mixing rules; also discusses models of blends as pseudo-pure fluids; of them, the paper recommends the mixture Helmholtz energy model of Lemmon and Jacobsen as the best available; presents a survey of data available for mixtures of R-32, R-125, R-134a, R-143a, R-152a, R-290, R-600, R-600a, and R-744; identifies further data needs; summarizes the status of Annex 18 to the Heat Pump Programme of the International Energy Agency (IEA) and provides an extensive list of references

M. O. McLinden, J. S. Gallagher, L. A. Weber, G. Morrison, D. Ward, A. R. H. Goodwin, M. R. Moldover, J. W. Schmidt, H. B. Chae, T. J. Bruno, J. F. Ely, and M. L. Huber (National Institute of Standards and Technology, NIST), **Measurement and Formulation of the Thermodynamic Properties of Refrigerants 134a (1,1,1,2-Tetrafluoroethane) and 123 (1,1-Dichloro-2,2,2-trifluoroethane),** paper 3282 (588-RP), *Transactions* (Annual Meeting, Vancouver, BC, 24-28 June 1989), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 95(2):263-283, 1989 (21 pages with 11 figures and 4 tables, RDB-0913)

Thermodynamic properties of R-134a and R-123 are formulated using a modified Benedict-Webb-Rubin (MBWR) equation of state fit to experimental measurements of the critical point, vapor pressure, saturated liquid and vapor volumes, superheated pressure-volume-temperature (PVT) behavior, and second virial coefficients derived from PVT and sound speed measurements. The heat capacity of the ideal gas reference state is determined from sound speed measurements on the low density vapor. Surface tensions are also presented. The experimental methods and results are summarized, compared to the property formulation, and compared to other sources in the literature. Tables and diagrams of the thermodynamic properties of R-123 and R-134a, prepared using the MBWR equation of state (EOS), are presented. While the various measurements cover different ranges of temperature and pressure, the MBWR formulation is applicable in both the liquid and vapor phases at pressures up to 10,000 kPa (1500 psia); the applicable temperature range is 233 to 450 K (-40 to 350 °F) for R-134a and 255 to 450 K (0 to 350 °F) for R-123. This paper summarizes the results of ASHRAE research project 588-RP.

K. Mecarik and M. Masaryk (Slovak Technical University, Czechoslovakia), **Thermodynamic Properties of Refrigerants R11, R12, R13, R14, R22, R23, R113, R114, R500, and R502,** *Heat Recovery Systems and CHP,* 11(2-3):193-197, 1991 (5 pages, rdb9924)

presents a set of equations and constants for calculating thermodynamic properties of R11, R-12, R-13, R-14, R-22, R-23, R-113, R-114, R-500, and R-502 in metric (SI) units; provides equation of state (EOS) and correlations for the saturated vapor pressure, liquid volume, specific heat capacity, enthalpy, and entropy

J. B. Mehl and A. R. H. Goodwin, **Measurement of the Dipole Moments of Seven Partially Fluorinated Hydrocarbons with a Radio-Frequency Reentrant Cavity Resonator**, *International Journal of Thermophysics,* 18(3):, 1996 (rdb8255)

physical properties

C. W. Meyer and G. Morrison (National Institute of Standards and Technology, NIST), **Dipole Moments of Seven Partially Halogenated Ethane Refrigerants**, *Journal of Physical Chemistry*, 95(9):3860-3866, 1991 (7 pages with 5 figures and 6 tables, available from JMC as RDB4969)

R-124, R-125, R-134, R-134a, R-143, R-143a, R-152a, R-740 (argon), thermodynamic properties, thermophysical data, dielectric constant, molar polarization, refractive index

C. W. Meyer and G. Morrison (National Institute of Standards and Technology, NIST), **Dipole Moments of Seven Refrigerants**, *Journal of Chemical and Engineering Data,* 36(4):409-413, 1991 (5 pages with 2 figures and 5 tables, RDB4970)

R-22, R-32, R-114, R-123, R-123a, R-E134, R-141b, thermodynamic properties, thermophysical data, dielectric constant, molar polarization, refractive index

R. C. Miller, A. D. Ceballos, K. R. Hall, and J. C. Holste (Texas A&M University), **Accurate Vapor Pressures for Refrigerants,** *Proceedings of the 1992 International Refrigeration Conference - En*ergy *Efficiency and New Refrigerants,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 2:479-487, July 1992 (9 pages with 3 figures and 2 tables, RDB2831)

thermodynamic properties, thermophysical data

J. Mollerup, **Thermodynamic Properties of Natural Gas, Petroleum Gas, and Related Mixtures: Enthalpy Predictions**, *Advances In Cryogenic Engineering,* 23:550-560, 1978 (11 pages, rdb7A59)

R-50 (methane), R-290 (propane), R-600 (n-butane), R-600a (isobutane), and others: hydrocarbon blends, thermophysical data

J. Mollerup, **Correlated and Predicted Thermodynamic Properties of LNG and Related Mixtures: Enthalpy Predictions**, *Advances in Cryogenic Engineering,* 20:172-194, 1972 (23 pages, rdb7A60)

R-50 (methane), R-170 (ethane), R-290 (propane), R-600 (n-butane), R-600a (isobutane), and others: hydrocarbon blends, liquified natural gas, thermophysical data

J. Morgenstern, I. Ebinger, J. Senst, and D. Vollmer (Hochschule für Verkehrswesen, Germany), **Thermodynamische Bewertung alternativer Kältemittel im Zusammenhang mit den TCKW-Restrikhonen** [Thermodynamic Properties of Alternative Refrigerants in Connection with Thermodynamic Restrictions], *Luft- und Kältetechnik,* 26:41-44, 1990 (5 pages in German, RDB8C52)

thermodynamic properties of R-124a and others; thermophysical data

G. Morrison (National Institute of Standards and Technology, NIST), **The Shape of the Temperature-Entropy Saturation Boundary**, *International Journal of Refrigeration* (IJR), 17(7):494-504, September 1994 (11 pages with 7 figures and 9 tables, RDB4A58)

role of the phase diagram in visualization, design, and analysis of refrigeration cycles: shape variation is a consequence of molecular structure; relationships to estimate the slope of the vapor branch of the T-S diagram; demonstrates a typical pattern of the shape leaning over toward increasing entropy as the molecule size increases, leading to re-entrant compression back into the two-phase region for isentropic or near-isentropic compression; thermodynamic properties for R-32, R-123, R-123a, R-124, R-E124, R-125, R-E125, R-134, R-134a, R-141b, R-142b, R-143, R-143a, R-E143a, R-152a, R-218, R-227ea, R-E227, R-236ea, R-236fa, R-236cb, R-245ca, R-245cb, R-E245, R-254cb, R-254fa, R-C270, R-290; thermophysical data

G. Morrison and M. O. McLinden (National Institute of Standards and Technology, NIST), **Azeotropy In Refrigerant Mixtures**, *International Journal of Refrigeration* (IJR), 16(2):129-138, February 1993 (10 pages with 7 figures and 4 tables, available from JMC as RDB3701)

This paper presents a method to predict the existence of binary azeotropes, noted as attractive "because they behave very nearly as pure materials." The paper presents data for 25 selected refrigerants, from which the existence of 65 azeotropes is predicted in 300 binary mixtures examined. Extensive compilations of information exist for 23 of them. The authors suggest that there may be promise for the remainder, for which no experimental information was found. The paper notes that the azeotropes found in the literature also were predictable by the method presented. The refrigerants examined include R-11, R-12, R-13B1, R-14, R-21, R-23, R-32, R-113, R-114, R-115, R-123, R-124, R-125, R-134, R-134a, R-141b, R-142b, R-143, R-143a, R-152a, R-218, R-C270, R-C318, and isopentane-2-methylbutane. The predicted azeotropes are categorized as shallow expected near the boiling point of the more volatile component, azeotropy extending to higher temperatures, and

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one associated with a Bancroft Point (in which the vapor pressures of the components at a particular temperature are identical).

J. D. Morrison, M. H. Barley, F. T. Murphy, I. B. Parker, and R. W. Wheelhouse (ICI Chemicals and Polymers, Limited, UK), **Use of an MHV-2 Equation of State for Modeling the Thermodynamic Properties of Refrigerant Mixtures**, *Preprints of the 12th Thermophysical Properties Symposium* (Boulder, CO, 19-24 June 1994), American Society of Mechanical Engineers (ASME), New York, NY, June 1994; republished in *CFCs, the Day After* (proceedings of the IIR meeting, Padova, Italy, 21-23 September 1994), International Institute of Refrigeration (IIR), Paris, France, 461 ff, September 1994; republished in the *International Journal of Thermophysics,* 16(5):1165-1174, September 1995 (10 pages, rdb6822)

development and application of a thermodynamic model based on the second-order, Modified Huron-Vidal (MHV-2) equation of state (EOS) to predict the properties of ternary blends of R-32, R-125, and R-134a (R-407 series): uses mixing rules to incorporate an activity-coefficient model for the excess Gibbs free energy; derives the parameters for the activity-coefficient model from experimental vapor-liquid equilibria (VLE) data for binary pairs of the components; results yield a thermodynamically consistent model that predicts the phase equilibria of R-32/125/134a blends; presents the input data used compared predicted values with experimental data; demonstrates use of the model to examine fractionation behavior for R-32/125/134a in during liquid charging and vapor leakage; discusses uses of the thermodynamic model

S. Y. Motta, S. L. Braga, J. A. R. Parise (Pontifíca Universidade Católica do Rio de Janeiro, Brazil), and R. P. Marques (Uberlândia Federal University, Brazil), **Vapor-Liquid Equilibrium Equations for Hydrocarbon-Oil Mixtures**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 441-446, July 1996 (6 pages with 8 figures and 1 table, RDB6C22)

R-290 and R-600a mixtures with lubricants; vapor-pressure correlations, Raoult's Law, Flory-Huggins polymer solution theory; vapor-pressure equation for R-290 and for R-600a; comparisons with experimental data

S. Nakagawa, T. Hori, H. Sato, and K. Watanabe (Keio University, Japan), **Isobaric Heat Capacity for Liquid 1-Chloro-1,1-difluoroethane and 1,1-Difluoroethane**, *Journal of Chemical and Engineering Data,* 38:70-74, 1992 (5 pages, RDB5473)

R-142b, R-152a, thermodynamic properties, thermophysical data

S. Nakagawa, H. Sato, and K. Watanabe (Keio University, Japan), **Isobaric Heat Capacity and Enthalpy for Liquid HFC-134a and HCFC-123**, *High Temperatures - High Pressures*, 23(2):191-198, 1991 (8 pages, rdb5482)

describes correlations of isobaric specific heat data for liquid R-123 and R-134a as functions of temperature and pressure using previously measured data; indicates that the liquid enthalpy surface derived from these correlations offers high accuracy

V. G. Niesen, L. J. Van Poolen, S. L. Outcalt, and C. D. Holcomb (National Institute of Standards and Technology, NIST), **Coexisting Densities and Vapor Pressures of Refrigerants R22, R134a, and R124 at 300 to 395 K**, *Fluid Phase Equilibria,* 97:81-95, 15 June 1994 (15 pages with 10 figures and 5 tables, RDB7A62)

presents measured coexisting densities and vapor pressures for R-22, R-124, and R-134a from 27 °C (80 °F) to near their respective critical points; also presents measurements of the compressed liquid and supercritical densities for R-22 and compares them to published data; reports that considerable discrepancies were found in the literature for the coexisting densities and vapor pressures of R-124 and R-134a

H. Nishiumi and T. Yokoyama, **Vapor-Liquid Equilibrium for the System of R134a-R22**, paper B105, *Proceedings of the 11th Japan Symposium on Thermophysical Properties*, 95-98, 1990 (4 pages, rdb7A29)

R-22/134a, VLE, thermodynamic properties, thermophysical data

K. Oguchi, T. Kogure, and T. Namiki (Kanagawa Institute of Technology, Japan), **Experimental Determination of the PVTX Properties of HFC-32/-HFC-125/HFC-134a**, *Proceedings of the 19th In*ternational *Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:442-449, 1995 (8 pages with 9 figures and 5 tables, RDB7845)

thermodynamic properties for the binary and ternary mixtures of R-32, R-125, R-134a with measurements for R-32/125 (75/25), R-32/-125/134a (23/25/52), R-32/125/134a (30/25/45), and R-125/134a (25/75); thermophysical data; fits to the Carnahan-Starling-DeSantis-Morrison (CSDM) equation of state (EOS)

K. Ohgaki, S. Umezono, and T. Katayama, **Pressure-Density-Temperature Relations of CHF_3, N_2O, and C_3H_6 in the Critical Region**, *Journal of*

Supercritical Fluids, 3:78-84, 1990 (13 pages, RDB-4B39)

R-23, R-744A (nitrous oxide), R-1270 (propene, propylene), thermodynamic properties, thermophysical data

M. Okada and Y. Higashi (Iwaki Meisei University, Japan), **Experimental Surface Tensions for HFC-32, HCFC-124, HFC-125, HCFC-141b, HCFC-142b, and HFC-152a**, *International Journal of Thermophysics,* 16(3):791-800, 1995 (10 pages, rdb7A08)

measurements of the surface tension of R-32, R-124, R-125, R-141b, R-142b, and R-152a: measurements were conducted under equilibrium conditions between the liquid and its saturated vapor; data were taken using the differential capillary-rise method (DCRM) for two glass capillary tubes in the temperature range from -3 to 67 °C (26-152 °F); the temperature dependence of the data were successfully represented by van der Waal correlations; compares the results to published data form other studies; transport properties, thermophysical data

M. Okada and Y. Higashi (Iwaki Meisei University, Japan), **Surface Tension Correlation of HFC-134a and HCFC-123,** *CFCs, the Day After* (proceedings of the IIR meeting, Padova, Italy, 21-23 September 1994), International Institute of Refrigeration (IIR), Paris, France, 541-548, September 1994 (8 pages, rdb7A09)

R-123 and R-134a: surface tension, transport properties, thermophysical data

M. Okada and Y. Higashi (Iwaki Meisei University, Japan), **Measurements of the Surface Tension for HCFC-124 and HCFC-141b**, *Proceedings of the 13th Japan Symposium on Thermophysical Properties*, Akita, Japan, 73-76, 1992 (4 pages, rdb3926)

R-124 and R-141b: transport data

M. Okada, Y. Higashi, T. Ikeda, and T. Kuwana (Iwaki Meisei University, Japan), **Measurements of the Surface Tension for HCFC-142b and HFC-152a**, *Proceedings of the 12th Japan Symposium on Thermophysical Properties*, 105-108, 1991 (4 pages, rdb3932)

R-142b and R-152a: thermodynamic and transport data

M. Okada (Nagaoka University of Technology, Japan), T. Umayahave, M. Hattori, and K. Watanabe (Keio University, Japan), **Measurements of the Surface Tension for R-123 and R-134a**, *Proceedings of the Tenth Japan Symposium on Thermophysical Properties* (20-22 September 1989), Shizuoka University, Japan, 60-62, 1989 (3 pages, rdb-8957)

R-123 and R-134a: thermodynamic and transport data

M. Okada (Nagaoka University of Technology, Japan) and K. Watanabe (Keio University, Japan), **Surface Tension Correlations for Several Fluorocarbon Refrigerants**, *Heat Transfer - Japanese Research,* Scripta Technica, Incorporated (Wiley Company), 17:35-52, 1988 (18 pages, rdb7956)

R-11, R-12, R-113, R-114, R-115, and others: transport properties, thermophysical data

M. Okada, M. Uematsu, and K. Watanabe (Keio University, Japan), **Orthobaric Liquid Densities of Trichlorofluoromethane, Dichlorodifluoromethane, Chlorodifluoromethane, 1,1,2-Trichlorotrifluoroethane, and 1,2-Dichiorotetrafluoroethane between 203 and 463 K**, *Journal of Chemical Thermodynamics,* 18:527-543, 1985 (17 pages, rdb-7C37)

R-11, R-12, R-22, R-113, and R-114: thermodynamic properties, thermophysical data

C. M. B. P. Oliveira and W. A. Wakeham, **The Viscosity of R32 and 8125 at Saturation**, *International Journal of Thermophysics,* 14(6):1131-1144, 1993 (14 pages, rdb4A52)

R-32, R-125, thermophysical properties, transport data

C. M. B. P. Oliveira and W. A. Wakeham, **The Viscosity of Five Liquid Hydrocarbons at Pressures up to 250 MPa**, *International Journal of Thermophysics*, 13:773-790, 1992 (18 pages, rdb8238)

thermophysical properties, transport data

V. P. Onischenko, V. P. Zhelezny, and B. P. Vladimirov (Odessa State Academy of Refrigeration, Ukraine), **Thermodynamical Properties of Binary Azeotropes of Ozone-Nondepleting Refrigerants**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:450-456, 1995 (7 pages with 3 figures and 4 tables, rdb7846)

experimental and theoretical property data for R-23, R-32, R-116, R-125, R-134a, R-152a, and their binary mixtures; azeotropes of R-218/134a, R-134a/152a, and R-23/116; thermodynamic properties, thermophysical data; fits to virial equations of state (EOS)

S. L. Outcalt and M. O. McLinden (National Institute of Standards and Technology, NIST), **Equations of State for the Thermodynamic Properties of R32**

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(**Difluoromethane) and R125 (Pentafluoroethane)**, *Preprints of the 12th Symposium on Thermophysical Properties* (Boulder, CO, 19-24 June 1994), American Society of Mechanical Engineers (ASME), New York, NY, June 1994; republished in *International Journal of Thermophysics,* 16(1):79-89, January 1995 (11 pages with 5 figures and 7 tables, RDB7844)

presents modified Benedict-Webb-Rubin (BWR) equations of state (EOSs) for R-32 and R-125; reports coefficients for the 32-term EOSs and for ancillary equations used to fit the ideal-gas heat capacities and the coexisting densities and pressures along the saturation boundaries; the MBWR coefficients were fit to measured pressure-volume-temperature (PVT) data, liquid heat capacities, second virial coefficients, and properties at coexistence; tabulates the prior studies by other investigators used as data sources to develop these equations; compares the predicted data to experimental values; indicates that the equations for R-32 and R-125 are accurately represent the data for -113 to 120 °C (-172 to 248 °F) and -99 to 175 °C (-147 to 347 °F), respectively, and for pressures up to 35 MPa (128 psia) and 68 MPa (9900 psia), respectively, with exception of the critical regions; also indicates that the EOSs give reasonable results for extrapolations to 227 °C (440 °F) and 60 MPa (8700 psia)

C-L. Peng, F. P. Stein, and A. S. Gow (Lehigh University), **Enthalpy-Based Cubic Equation of State Mixing Rule for Cross-Prediction of Excess Thermodynamic Properties of Hydrocarbon and Halogenated Refrigerant Mixtures**, *Fluid Phase Equilibria,* 108(1-2):79-102, July 1995 (24 pages, rdb8919)

presents mixing rules for Soave's equation of State (EOS) based on excess enthalpy for binary blends: casts the Soave-Kwong-Redlich (SRK) EOS in a form that separates the constants from the pressure, volume, and temperature parameters, yielding an equation with two volume parameters and one energy-volume parameter; derives an expression for the binary excess enthalpy; determines a limit for infinite pressure to provide an expression with explicit composition and temperature terms using conventional linear mixing rules; uses the mixing rules with published excess enthalpy data to predict vapor-liquid equilibria (VLE) properties for eleven binary systems comprised of simple aliphatic and halogenated hydrocarbons

S. G. Penoncello, R. T. Jacobsen, K. M. de Reuck, A. E. Elhassan, R. C. Williams, E. W. Lemmon (University of Idaho), **Selection of International Standards for the Thermodynamic Properties of HFC-134a and HCFC-123,** *International Journal of Thermophysics,* 16(3):781-790, May 1995 (10 pages, rdb8223)

summarizes the objectives and activities of the International Energy Agency (IEA) Heat Pump Programme Annex 18: reviews three equations of state (EOS) for R-123 and four for R-134a by independent researchers in Germany, Japan, and the United States; presents the formulations selected based on accurate representation of experimental data and thermodynamic consistency

R. A. Perkins, A. Laesecke (National Institute of Standards and Technology, NIST, USA), and C. A. Nieto de Castro (Universidade de Lisboa, Portugal), **Polarized Transient Hot Wire Thermal Conductivity Measurements,** *Fluid Phase Equilibria,* 80:-275-286, 1992 (12 pages with 5 figures and 3 tables, available from JMC as RDB3709)

thermodynamic properties of R-134a and R-142b; thermophysical data

R. W. Powell, B. W. Joliffe, R. P. Tye, and A. E. Langton, **The Thermal Conductivities of Some Liquid Refrigerants**, annex to the *Bulletin of the International Institute of Refrigeration,* (2):79-88, 1966 (10 pages, rdb8435)

thermal conductivity measurements by a thermal comparator technique for R-123 and others: transport properties, thermophysical data

C-C. Piao, I. Iwata, and M. Noguchi (Daikin Industries, Limited, Japan), **Thermodynamic Properties of HFC-32, HFC-125, and HFC-134a Mixtures**, *Fluid Phase Equilibria,* 150-151(0):313-322, 1998 (10 pages with 10 figures and 1 table, RDB8C25)

presents an equation of state (EOS) for R-32/125 (R-410 series), R-32/134a, R-125/134a, and R-32/125/134a (R-407 series) blends determined from available pressure-volume-temperature (PVT), vapor-liquid equilibrium (VLE), heat capacity, and speed of sound measurements; indicates that the EOS is valid for VLE conditions, superheated vapors, and compressed liquid phases for -73 to 197 °C (-100 to 386 °F) and pressures up to 20 MPa (2900 psia); the EOS is based on 18-coefficient modified Benedict-Webb-Rubin (MBWR) equations for the components with new mixing rules; compares calculated properties to experimental data; thermophysical data

C-C. Piao, I. Iwata, K. Fujiwara, and M. Noguchi (Daikin Industries, Limited, Japan), **A Study of Thermodynamic Properties of HFC-32/125/134a Ternary Mixture**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:488-495, 1995 (8 pages with 4 figures and 6 tables, RDB7850)

18 coefficient, modified Benedict-Webb-Rubin (BWR) equations of state (EOS) and critical parameters (density, pressure, and temperature) for R-32, R-125, and R-134a; mixing rule equations for the superheated gaseous phase of R-32/125, R-32/125/134a, and R-32/134a blends; Peng-Robinson (PR) EOS for their two-phase pressure-volume-temperature-concentration (PVTx) properties; modified Hankinson-Brobst-Thomson (HBT) to represent the vapor-liquid equilibrium (VLE) and saturated liquid densities; summary thermodynamic property tables for R-32/134a (30/70), R-407C [R-32/125/134a (23/-25/52)], and R-410A [R-32/125 (50/50)]; derived performance in ideal cycles at representative conditions for air conditioning shows performance to decline from R-32/134a (30/70) to R-407C and R-410A by 4.5 and 10.7%, respectively, while capacity increases by 1.2 and 44%, respectively, for constant volumetric flow (compressor displacement); equations are valid for the cited blends for -33 to 98 °C (-28 to 350 °F) and pressures up to 8 MPa (1200 psia)

I. B. Rabinovich and B. V. Lebedev, **On the Thermodynamic Stability of Polyisobutylene**, *Tr. Khim. Khim. Tekhnol.,* Russia (then USSR), 194-196, 1971 (3 pages, rdb8913)

thermodynamic properties of isobutene; thermophysical data

W. Rathjen and J. Straub (Technische Universität München, TUM, Germany), **Surface Tension and Refractive Index of Six Refrigerants from the Triple Point up to the Critical Point**, *Proceedings of the Seventh Thermophysical Properties Symposium*, American Society of Mechanical Engineers (ASME), New York, NY, 839 ff, 1977 (rdb8235)

thermodynamic properties, thermophysical data

R. C. Reid, J. M. Prausnitz, and B. E. Poling, **The Properties of Gases and Liquids** (fourth edition), McGraw-Hill Book Company, New York, NY, 1987 (rdb3239)

widely cited reference on physical, thermodynamic, and transport properties; thermophysical data

K. Reuter, S. Rosenzweig, and E. U. Frank, **The Static Dielectric Constant of CH_3F and CHF_3 at 468 K and 2000 Bar**, *Physica A*, 156:294-302, 1989 (9 pages, rdb4B40)

R-23, R-41, physical properties

D. Ripple and D. R. Defibaugh (National Institute of Standards and Technology, NIST), **Viscosity of the Saturated Liquid Phase of Three Fluorinated Ethanes: R152a, R143a, and R125**, *Journal of Chemical and Engineering Data,* 42:360-364, 1997 (5 pages with 5 figures and 5 tables, RDB8236)

transport properties for R-125, R-143a, and R-152a: viscosity measurements with a straight capillary viscometer constructed of stainless steel and sapphire for -18 to 50 °C (-1 to 122 °F); describes the apparatus and free-volume model used to correlate the data; compares the measured results to those found in other studies; notes that systematic effects, such as surface tension influences in capillary viscometers or adsorption effects in vibrating wire viscometers, may be as important in accounting for differences as impurities in the samples measured

K. Ruzicka and V. Majer, **Simultaneous Treatment of Vapor Pressures and Related Thermal Data between the Triple and Normal Boiling Point Temperatures for n-Alkanes of C_5-C_{20}**, *Journal of Physical and Chemical Reference Data*, 23(1):1-39, 1994 (39 pages, rdb7B30)

thermodynamic properties of R-601 (pentane), R-602 (hexane), and larger hydrocarbons; thermophysical data

V. Ruzicka, Jr., and E. S. Domalski, **Estimation of the Heat Capacities of Organic Liquids as a Function of Temperature Using Group Additivity. I. Hydrocarbon Compounds**, *Journal of Physical and Chemical Reference Data*, 22(3):597-618, 1993 (22 pages, rdb7968)

liquid specific heat, thermodynamic properties, thermophysical data

V. Ruzicka, Jr., and E. S. Domalski, **Estimation of the Heat Capacities of Organic Liquids as a Function of Temperature Using Group Additivity. II. Compounds of Carbon, Hydrogen, Halogens, Nitrogen, Oxygen, and Sulfur**, *Journal of Physical and Chemical Reference Data*, 22(3):619-657, 1993 (39 pages, rdb7969)

liquid specific heat, thermodynamic properties, thermophysical data

B. Saager and J. Fischer (Ruhr-Universität, Germany), **Construction and Application of Physically Based Equations of State, Part III. Correlative and Predictive Application to the Refrigerants R22 and R152a**, *Fluid Phase Equilibria,* 93:101-140, 11 February 1994 (40 pages, rdb8935)

applies a set of equations of state (EOSs) with four or five parameters, for which the Helmholtz energy is given as the sum the of the hard body contribution and the influences of attractive dis-

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persion forces and polar interactions, to R-22 and R-152a

T. Sako, M. Yasumoto, M. Sato, O. Kitao (National Institute of Materials and Chemical Research, NIMC, Japan), R. Yamamoto (Kyoto University), K. Ishiguro, and M. Kato (Nihon University), **Thermodynamic Properties of Fluorinated Ethers as Alternative Refrigerants,** paper 205, *Molecular Thermodynamics and Molecular Simulation* (MTMS'97, proceedings of the 17th International Symposium of Hosei University Tokyo, Japan, 12-15 January 1997), 102-108, 1997 (7 pages with 6 figures and 3 tables, RDB8703)

measurements of the normal boiling point and critical properties (temperature, pressure, and density) of hydrofluoroether (HFE) and fluorinated amine candidates for refrigerant use; comparisons to prediction methods; provides data for R-E134, R-E227ea1, R-E245ca2, R-E329mcc2, R-E338mmz1, and R-E356mmz1 as well as $NCH_3(CF_3)_2$, $NCHF_2(CF_3)_2$, and NCH_3-$CH_2(CF_3)_2$; concludes that the Lydersen method provides a good estimation for critical properties, but that several group contribution methods examined are inadequate to estimate the normal boiling point; thermodynamic properties; thermophysical data

T. Sako, M. Sato, N. Nakazawa, M. Oowa, H. Yasumoto, H. Ito, and S. Yamashita (National Institute of Materials and Chemical Research, NIMC, Japan), **Thermodynamic Properties of Fluorinated Ethers as Alternative Refrigerants**, *Journal of Chemical and Engineering Data*, 41(4):802-805, 1996 (4 pages, rdb8322)

thermodynamic properties of R-E245cb1 and other fluoroether (FE) and hydrofluoroether (HFE) candidates for refrigerant use; thermophysical data

T. Sako, M. Sato, N. Nakazawa, M. Oowa, A. Sekiya, H. Ito, and S. Yamashita (National Institute of Materials and Chemical Research, NIMC, Japan), **Thermodynamic Properties of Fluorinated Ethers as Alternative Refrigerants**, *Sci. Tech. Froid*, 485-491, 1994 (7 pages, rdb8316)

thermodynamic properties of fluoroether (FE) and hydrofluoroether (HFE) candidates for refrigerant use; thermophysical data

J. R. Sand, S. K. Fischer (Oak Ridge National Laboratory, ORNL), and J. A. Jones (Jet Propulsion Laboratory, JPL, California Institute of Technology), **Carnahan-Starling-Desantis and Lee-Kesler-Plöcker Interaction Coefficients for Several Binary Mixtures of Ozone-Safe Refrigerants**, *International Journal of Refrigeration* (IJR), 17(2):123-129, February 1994 (7 pages with 2 figures and 3 tables, RDB4203)

Estimates of interaction coefficients (ICs) are provided for binary refrigerant blends for both the Carnahan-Starling-Desantis (CSD) and Lee-Kesler-Plöcker (LKP) equations of state (EOS). These IC values characterize the non-ideal behavior of mixtures, and are useful in calculating thermodynamic properties. The estimates were determined by least-squares fits of the CSD and LKP equations to previously measured, saturated vapor pressure (bubble point) data. 70 mixtures of 8 different refrigerants in 18 binary combinations were analyzed. The combinations included R-12/152a, R-22/124, R-22/134, R-22/134a, R-22/142b, R-22/152a, R-23/22, R-23/134a, R-124/142b, R-134/124, R-134/142b, R-134a/124, R-134a/134, R-134a/142b, R-134a/152a, R-152a/124, R-152a/134, and R-152a/142b. The paper describes the use of IC values, experimental apparatus used to measure the data, presents the resulting ICs, and discusses variances found with previously determined values. Good agreement was found for several known blends, but poor agreement resulted for the well characterized R-22/142b blend; further experimental verification is recommended. Comparisons between experimental ICs and those calculated from physical properties or critical constants of the components suggest that refinement of the property calculation algorithms may be desirable.

H. Sato and K. Watanabe (Keio University, Japan), **Thermodynamic Property Database for New Refrigerants**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:519-526, 1995 (8 pages with 6 figures and 4 tables, RDB7858)

describes a database to consolidate experimental data, source and executable computer programs and more than 700 scientific papers on thermodynamic properties; pressure-volume-temperature (PVT) properties, isobaric specific heats, sound speeds, virial coefficients, and ideal gas heat capacities for R-32, R-125, R-134a, and blends of R-32/125 and R-32/134a

G. Scalabrin, L. Garavello (Università di Padova, Italy), and R. Camporese (Consiglio Nazionale della Ricerche, CNR, Italy), **Prediction of the Thermal Conductivity of Pure Refrigerants Through an Extended Corresponding States Model,** *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 415-422, July 1996 (6 pages with 11 figures and 5 tables, RDB6C17)

extended corresponding states (ECS) model [used in REFPROP 4.01] for prediction of thermodynamic properties of single-compound refrigerants and blends; density and thermal conductivity; comparisons of experimental and predicted data for R-32, R-125, R-134a, R-143a, and R-152a

P. Scharlin and R. Battino (University of Turku, Finland), **Solubility of CCl_2F_2, $CClF_3$, CF_4 and c-C_4F_8 in H_2O and D_2O at 288 to 318 K and 101.325 kPa. Thermodynamics of Gases from H_2O to D_2O**, *Fluid Phase Equilibria,* 95:137-147, 8 April 1994 (11 pages, rdb8931)

presents measurements of the solubilities of R-12, R13, R-14, and R-C318 in normal and heavy water (H_2O and D_2O, respectively) at four temperatures in the range 15-45 °C (59-113 °F) and at a partial pressure of gas of 101.325 kPa (14.7 psia): measurements used a computer-controlled Ben-Naim/Baer apparatus with an estimated precision of 0.5-1.0%; the experimental data were processed using rigorous thermodynamic methods and were fitted to the Clarke-Glew-Weiss equation; changes in the thermodynamic properties on solution were calculated from smoothing equations; thermodynamic transfer functions of gases from H_2O to D_2O were calculated; changes induced by the solvation process on the structure of water were estimated from the Gibbs energy of transfer and the difference in the hydrogen bond energies for D_2O and H_2O

J. W. Schmidt, E. Carillo-Nava, and M. R. Moldover (National Institute of Standards and Technology, NIST), **Partially Halogenated Hydrocarbons $CHFCl$-CF_3, CF_3-CH_3, CF_3-CHF-CHF_2, CF_3-CH_2-CF_3, CHF_2-CF_2-CH_2F, CF_3-CH_2-CHF_2, and CF_3-O-CHF_2: Critical Temperature, Refractive Indices, Surface Tension and Estimates of Liquid, Vapor and Critical Densities**, *Fluid Phase Equilibria*, 122(1-2):187-206, 31 July 1996 (10 pages with 4 figures and 5 tables, RDB7714)

thermodynamic properties for R-124, R-E125, R-143a, R-236ea, R-236fa, R-245ca, and R-245fa: measurements of the critical temperatures, refractive indices, and capillary rise for these fluids; refractive indices were combined with reference densities to determine the Lorentz-Lorenz constants, from which estimates were made of the vapor and liquid densities up to the critical points; surface tensions were determined from these densities and the capillary rise measurements; thermophysical data

J. W. Schmidt and M. R. Moldover (National Institute of Standards and Technology, NIST), **Alternative Refrigerants CH_2F_2 and C_2HF_5: Critical Temperature, Refractive Index, Surface Tension, and Estimates of Liquid, Vapor, and Critical Densities**, *Journal of Chemical and Engineering Data*, 39(1):39-44, 1994 (6 pages with 6 figures and 4 tables, RDB7A13)

thermodynamic and transport properties of R-32 and R-125: reports refractive index and capillary rise for 23 °C (73 °F) to their critical points along with the critical temperatures and the temperature-dependent capillary lengths; combines the refractive index with liquid density data at 30 °C (86 °F) to determine the Lorentz-Lorenz constant; this constant and the data were used to estimate the liquid, vapor, and critical densities and the surface tensions up to the critical points

J. W. Schmidt and M. R. Moldover (National Institute of Standards and Technology, NIST), **Structure of the Vapor-Liquid Interface Near the Critical Point**, *Journal of Chemical Physics*, 99(1):582-589, 1 July 1993 (8 pages with 8 figures and 1 table, RDB8941)

thermodynamic properties of R-23, R-744, and R-7146 at their critical points: thermophysical data

A. M. Silva and L. A. Weber (National Institute of Standards and Technology, NIST), **Ebulliometric Measurement of the Vapor Pressure of 1-Chloro-1,1-difluoroethane and 1,1-Difluoroethane**, *Journal of Chemical and Engineering Data*, 38(4):644-646, 1993 (3 pages with 4 figures and 3 tables, RDB4911)

This paper presents measured vapor pressure data for R-142b between -48 and 12 °C (-55 and 53 °F) and for R-152a between -53 and 0 °C (-64 and 32 °F). It describes a comparative ebulliometer used for the measurements. The paper shows and tabulates deviations of the measured data from fits to an Antoine equation and, for R-152a, also to a Wagner equation. It compares the findings to those published by others, some of which were used in fitting the new data. The results offer a means to predict the vapor pressure of R-142b from -73 to 27 °C (-100 to 80 °F) and of R-152a from -58 to the critical temperature, near 113 °C (-73 to 235 °F).

R. R. Singh, E. A. E. Lund, and I. R. Shankland (AlliedSignal Incorporated), **Thermophysical Properties of HFC-32, HFC-125, and HFC-32/HFC-125**, *Proceedings of the International CFC and Halon Alternatives Conference* (Baltimore, MD, 3-5 December 1991), Alliance for Responsible CFC Policy, Arlington, VA, 451-459, 1991 (10 pages with 3 figures and 4 tables, available from JMC as RDB-2234)

This paper provides a summary of thermodynamic data for the vapor, compressed liquid, and saturated regions of R-32, R-125, and R-32/125 (60/40).Correlations based on mea-

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sured data and the Martin Hou equation of state are given for vapor pressure, liquid density, and ideal gas heat capacity. The paper briefly describes a pseudo-isochoric (constant mass) pressure-volume-temperature (PVT) apparatus; this new, automated apparatus was used to obtain some of the data presented. Tables present the boiling point temperature; critical point temperature, pressure, and density; and molecular mass. Pressure-enthalpy (Mollier) diagrams also are provided for the two single-compound refrigerants and their 60/40 blend.

A. Stegou-Sagia, **Thermodynamic Property Formulations and Heat Transfer Aspects for Replacement Refrigerants: R-123 and R-134a**, *Fuel And Energy Abstracts,* 38(5):347, September 1997 (1 page, rdb8C28)

thermodynamic properties of R-123 and R-134a; thermophysical data

K. H. U. Ström and U. B. Grén (Chalmers University of Technology, Sweden), **Liquid Molar Volume of CH_2FCF_3, CH_3CClF_2, and CH_3CHF_2, and the Mixtures CHF_2Cl + CH_3CClF and CHF_2Cl + CH_3CHF_2**, *Journal of Chemical and Engineering Data*, 38(2):254-256, 1993 (3 pages with 2 figures and 2 tables, rdb7105)

thermodynamic properties of R-134a, R-142b, R-152a, R-22/142b, and R-22/152a; thermophysical data

L-Q. Sun, M-S. Zhu, L-Z. Han, and Z-Z. Lin (Tsinghua University, China), **Thermal Conductivity of Gaseous Difluoromethane and Pentafluoroethane near the Saturation Line,** *Journal of Chemical and Engineering Data*, 42(1):179-182, 1997 (4 pages with 8 figures and 3 tables, RDB8C21)

measurements of the vapor thermal conductivity of R-32 for -19 to 69 °C (-2 to 155 °F) and of R-125 near the saturation line for -22 to 61 °C (-7 to 141 °F): the thermal conductivities were measured with a transient hot-wire instrument with an estimated uncertainty of 3%: the paper presents correlations of the data to temperature and comparisons of the results to data in published findings from other studies

L-Q. Sun, M-S. Zhu, L-Z. Han, and Z-Z. Lin (Tsinghua University, China), **Viscosity of Difluoromethane and Pentafluoroethane along the Saturation Line**, *Journal of Chemical and Engineering Data*, 41(2):292-296, 1996 (5 pages with 6 figures and 5 tables, RDB8C20)

measurements of the viscosity of R-32 for -40 to 60 °C (-40 to 140 °F) and of R-125 along the saturation line for -40 to 55 °C (-40 to 132 °F) in a calibrated capillary viscometer; presents correlations of the data to temperature and compares the result to published findings by other investigators; concludes that the uncertainty of the results is no more than 3%

T. Takagi, **Ultrasonic Speed for Liquid Trichlorofluoromethane and 1,1-Dichloro-2,2,2-trifluoroethane** [2,2-Dichloro-1,1,1-trifluoroethane] **at Temperatures from 283 to 373 K and Pressures up to 75 MPa**, *Journal of Chemical and Engineering Data*, 35:381 ff, 1991 (rdb7966)

R-11 and R-123: speed of sound, thermodynamic properties, thermophysical data

Y. Tanaka, S. Matsuo, and S. Taya, **Gaseous Thermal Conductivity of Difluoromethane (HFC-32), Pentafluoroethane (HFC-125), and their Mixtures**, *International Journal of Thermophysics,* 16:121-131, 1995 (11 pages, rdb8956)

transport properties of R-32, R-125, and R-32/125 (R-410 series): thermal conductivity; viscosity; thermophysical data

Y. Tanaka, M. Nakata, and T. Makita (Kobe University, Japan), **Thermal Conductivity of Gaseous HFC-134a, HFC-143a, HCFC-141b, and HCFC-142b**, *International Journal of Thermophysics,* 12(6):949-963, 1991 (15 pages, rdb5488)

R-134a, R-141b, R-142b, R-143a, transport properties, thermophysical data

B. Taxis and K. Stephan (Universität Stuttgart, Germany), **Application of the Transient Hot-Wire Method to Gases at Low Pressures**, *International Journal of Thermophysics,* 15(1):141-153, 1994 (13 pages, rdb8466)

thermal conductivity measurements of R-123 and others; transport properties; thermophysical data

A. S. Teja and P. Rice, **Generalized Corresponding States Method for the Viscosities of Liquid Mixtures**, *Industrial Engineering Chemistry Fundamentals,* 20:77-81, 1981 (5 pages, rdb8904)

transport properties, thermophysical data

A. S. Teja and A. Singh, **Equation of State for Ethane, Propane, and n-Butane**, *Cryogenics*, 17(11):591-596, 1977 (6 pages, rdb5717)

thermodynamic properties of R-170, R-290, and R-600; thermophysical data

M. J. Terry, J. T. Lynch, M. Bunclark, K. R. Mansell, and L. A. K. Staveley, **The Densities of Liquid Argon, Krypton, Xenon, Oxygen, Nitrogen, Carbon Monoxide, Methane, and Carbon Tetrafluoride Along the Orthobaric Liquid Curve**, *Journal of Chemical Thermodynamics*, 1:413-424, 1969 (12 pages, rdb7C08)

R-14 (tetrafluoromethane, carbon tetrafluoride), R-50 (methane), R-728 (nitrogen), R-732 (oxygen), R-740 (argon), R-784 (krypton), R-7131 (xenon), and carbon monoxide: thermodynamic properties, thermophysical data

J. R. Thorne (International Technical Services, Italy), **Comprehensive Thermodynamic Approach to Modeling Refrigerant-Lubricant Oil Mixtures**, *HVAC&R Research,* 1(2):110-126, April 1995 (17 pages with 3 figures and 6 tables, rdb7A28)

prediction of bubble-point temperatures, local oil concentrations, liquid specific heats, and enthalpy changes during evaporation; method allows determination of the effect of the lubricant on the log-mean temperature difference (LMTD) of evaporators and provides a basis for further advances in heat transfer research and design

R. Tillner-Roth, **Die thermodynamischen Eigenschaften von R152a, R134a, und ihren Gemischen - Messungen und Fundamentalgleichungen** [The Thermodynamic Properties of R-152a, R-134a, and Their Mixtures - Measurements and Fundamental Equations], Doktor-Ingenieur [Doctor of Engineering] thesis, Universität Hannover, Hannover, Germany, 1993; republished as research report 41, Deutscher Kälte- and Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Stuttgart, Germany, 1994 (in German, rdb7A14)

thermodynamic properties of R-134a, R-152a, and R-134a/152a blends: fundamental equation (FEQ); thermophysical data

O. B. Tsvetkov, Y. A. Laptev, and A. G. Asambaev (Saint Petersburg State Academy of Refrigeration and Food Technologies, Russia), **Thermal Conductivity of Refrigerants R123, R134a, and R125 at Low Temperature**, *International Journal of Thermophysics,* 15(2):203-214, 1994 (12 pages, rdb4B27)

transport properties of R-123, R-125, and R-134a; thermophysical data

M. Türk, J. Zhai, M. Nagel, and K. Bier (Technische Universität Karlsruhe, Germany), **Messung des Dampfdruckes und der Kritischen Zustandsgrößen von neuen Kältemittlen** [Measurement of the Vapor Pressure and the Critical Properties of New Refrigerants], *Fortschritt-Berichte VDI*, VDI-Verlag, Düsseldorf, Germany, 19(79), 1994 (in German, rdb8C50)

thermodynamic properties, thermophysical data

Y. Ueno, Y. Kobayashi, Y. Nagasaka, and A. Nagashima, **Thermal Conductivity of CFC Alternatives: Measurements of HCFC-123 and HFC-134a in the Liquid Phase by the Transient Hot Wire Method**, *Nippon Kikai Gakkai Ronbunshu* (Transactions of the Japan Society of Mechanical Engineers, JSME), JSME, Tokyo, Japan, B57:3169-3175 also cited as B57:309-315, 1991 (7 pages in Japanese, rdb4B57)

transport properties of R-123 and R-134a; thermophysical data

L. J. Van Poolen (Calvin College), C. D. Holcomb (National Institute of Standards and Technology, NIST), and V. G. Niesen (Conoco Incorporated), **Critical Temperature and Density from Liquid-Vapor Coexistence Data: Application to Refrigerants R32, R124, and R152a**, *Fluid Phase Equilibria*, 129:105-111, 1997 (7 pages with 3 tables, RDB9125)

measurements of liquid-vapor coexisting density and temperature to within 3-20 °C (5-36 °F) of the critical point temperatures; calculation of the critical densities and temperatures of R-32, R-124, and R-152a

L. J. Van Poolen, V. G. Niesen, C. D. Holcomb, and S. L. Outcalt (National Institute of Standards and Technology, NIST), **Critical Densities from Coexisting Density Data: Application to Refrigerants R22, R134a, and R124**, *Fluid Phase Equilibria,* 97:97-118, 15 June 1994 (22 pages with 7 figures and 6 tables, RDB8925)

presents the critical densities for R-22, R-124, and R-134a: derives appropriate forms of the rectilinear diameter for coexisting densities based on a mass balance and the behavior of the critical liquid volume fraction; discusses the need for a single temperature-dependent term in the rectilinear diameter to fit experimental vapor and liquid coexisting densities; summarizes development of internal consistency tests of coexistence density data and critical density values; concludes that the resulting critical density values, namely 523.65 ±1.07 kg/m^3 for R-22, 559.76 ±1.54 kg/m^3 for R-124, and 513.02 ±1.98 kg/m^3 for R-134a are in good agreement with published values and with values calculated from published coexistence density data

B. P. Vladimirov and Y. F. Shvets, **Saturated Vapor Pressure of R-218 and R-329 and Azeotropic Mixtures of R-116 and R-23**, *Teplofizicheskie Svoistva Veshchestv i Materialov* [Thermophysical Properties of Substances and Materials], Izdatel'stvo Standartov, Moscow, Russia, 28:24-27, 1989 (4 pages with 1 figure and 4 tables, in Russian, RDB3C11)

thermodynamic properties of R-218, R-329, R-23/116 (35.79/63.76 + 0.45 impurities) [R-508 series]: property measurements and regression

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equations for vapor pressure calculations; thermophysical data

L. A. Weber and A. M. Silva (National Institute of Standards and Technology, NIST), **Design of a High-Pressure Ebulliometer, with Vapor-Liquid Equilibrium Results for the Systems CHF_2Cl + CF_3-CH_3 and CF_3-CH_2F + CH_2F_2**, *International Journal of Thermophysics,* 17(4):873-888, July 1996 (16 pages with 5 figures and 3 tables, RDB8213)

presents thermodynamic property measurements for R-32/134a and R-143a/22 taken with a new, high-pressure, metal ebulliometer; compares the results to calculations with a Peng-Robinson (PR) equation of state (EOS) and to published data for R-32/134a; concludes that use of the Wilson activity coefficient model provides a good description of the liquid-phase activity coefficients for systems of organic fluorochemicals, but notes discrepancies among published studies in the data for R-32/134a; thermophysical data

L. A. Weber (National Institute of Standards and Technology, NIST), **Model for Calculating Virial Coefficients of Natural Gas Hydrocarbons with Impurities**, *Fluid Phase Equilibria,* 111(1):15-26, October 1995 (12 pages with 7 figures and 1 table, RDB7C60)

This paper applies a model for calculating second and third virial coefficients to systems of natural gas hydrocarbons and their common impurities, namely carbon dioxide, carbon monoxide, hydrogen sulfide, nitrogen, and water. The model was originally developed to describe the behavior of polar halocarbon refrigerants and their mixtures. It can be used to correlate thermophysical data, identify probable errors, and provide data predictions. It also can be used to calculate gas-phase densities, thermodynamic properties, fugacities, and input data for global equations of state. The paper gives examples for some of the pure components and for the binary systems R-170/H_2S (ethane, hydrogen sulfide) and R-50/718 (methane/water).

L. A. Weber and A. M. Silva (National Institute of Standards and Technology, NIST), **Measurements of the Vapor Pressures of Difluoromethane, 1-Chloro-1,2,2,2-tetrafluoroethane, and Pentafluoroethane**, *Journal of Chemical and Engineering Data,* 39(4):808-812, October 1994 (5 pages with 4 figures and 5 tables, RDB8217)

presents measurements of the vapor pressures of R-32 for -38 to -8 °C (-37 to 17 °F), R-124 (2-chloro-1,1,1,2-tetrafluoroethane) for -53 to 13 °C (-64 to 55 °F); and R-125 for -55 to 13 °C (-67 to 55 °F): measurements were made in ebulliometers, one of an Ambrose type made of glass and one of all-metal construction for pressures exceeding 260 kPa (38 psia); also presents calculated vapor pressures for R-125 for temperatures down to -103 °C (-154 °F); examines the azeotropic mixture of R-125/115 and describes an adjustment to the R-125 data to correct for a small impurity of R-115; thermophysical data

L. A. Weber (National Institute of Standards and Technology, NIST), **Ebulliometric Measurement of the Vapor Pressures of R-123 and R-141b**, *Fluid Phase Equilibria,* 80:141-148, 1992 (8 pages with 4 figures and 3 tables, RDB4569)

measurements of the vapor pressures of R-123 and R-141b by comparative ebulliometry technique for -3 to 39 °C (26 to 102 °F) and 25-129 kPa (4-19 psia); descriptions of the apparatus used; tabulated raw data and comparisons to published data; thermodynamic properties; thermophysical data

J. V. Widiatmo, H. Sato, and K. Watanabe (Keio University, Japan), **Experimental Thermodynamic Properties of Alternative Mixtures Including R-32, R-125, and R-134a Refrigerants**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:614-621, 1995 (8 pages with 8 figures and 2 tables, rdb7906)

R-32/125, R-32/125/134a, R-32/134a, R-125/-134a, binary interaction coefficients for a Peng-Robinson (PR) and the modified Hankinson-Brobst-Thomson (HBT) equations of state (EOSs), thermodynamic properties, thermophysical data

J. V. Widiatmo and K. Watanabe (Keio University, Japan), **Saturated-Liquid Densities and Vapor Pressures of 1,1,1-Trifluoroethane**, **Difluoromethane, and Pentafluoroethane**, *Journal of Chemical and Engineering Data,* 39:304-308, 1994 (5 pages, rdb8256)

thermodynamic properties of R-32, R-125, and R-143a; thermophysical data

J. V. Widiatmo, H. Sato, and K. Watanabe (Keio University, Japan), **Saturated-Liquid Densities and Bubble Point Pressures of the Binary System HFC 32 + HFC 125**, *High Temperatures -High Pressures,* 25:677-683, 1993 (7 pages, rdb7860)

thermodynamic properties R-32/125 (R-410 series); thermophysical data

J. V. Widiatmo, H. Sato, and K. Watanabe (Keio University, Japan), **Measurement of Vapor Pres-**

sures and Liquid Densities of HFC-32 and HFC-125, *Proceedings of the Third Asian Thermophysical Properties Conference* (Beijing, People's Republic of China), 364-369, 1992 (6 pages, rdb5456)

thermodynamic properties of R-32 and R-125; thermophysical data

R. Yamamoto, S. Matsuo, and Y. Tanaka, **Thermal Conductivity of Halogenated Ethanes HFC-134a, HCFC-123, and HCFC-141b**, *International Journal of Thermophysics*, 14:79-90, 1993 (12 pages, rdb8464)

thermal conductivity of R-123, R-134a, and R-141b: transport properties, thermophysical data

J. Yata, M. Hori, T. Kurahashi, and T. Minamiyama, **Thermal Conductivity of Alternative Fluorocarbons in Liquid Phase**, *Fluid Phase Equilibria*, 80(11):287-296, 1992 (10 pages, rdb3928)

R-141b, R-142b, R-152a; thermophysical data

J. Yata, M. Hori, and T. Minamiyama, **Refractive Index of HCFC-22 and HFC-134a**, *Proceedings of the Eleventh Japan Symposium on Thermophysical Properties*, 1990 (rdb4B43)

R-22, R-134a, transport properties, thermophysical data

J. Yata, C. Kawashima, M. Hori, and T. Minamiyama, **Thermal Conductivity of R123 and R134a in Liquid Phase**, *Proceedings of the Second Asian Thermophysical Properties Conference* (Sapporo, Japan), 201-205, 1989 (5 pages, rdb4B44)

R-123, R-134a, thermodynamic data

C. Yokoyama and S. Takahashi, **Saturated Liquid Density for R123, R123a, and R-134a**, *Proceedings of the 29th High Pressure Conference* (Fujisawa, Japan, 16-18 November 1988), 116-117, 1988 (2 pages, rdb9137)

thermodynamic properties of R-123, R-123a, and R-134a; thermophysical data

B. A. Younglove and J. F. Ely (National Institute of Standards and Technology, NIST), **Thermophysical Properties of Fluids. II. Methane, Ethane, Propane, Isobutane, and Normal Butane**, *Journal of Physical and Chemical Reference Data*, 16(4):577-765 (possibly 577-798), 1987 (188 pages, rdb7840)

thermodynamic properties of R-50, R-170, R-290, R-600a, and R-600: hydrocarbons; thermophysical data

B. A. Younglove, **Thermophysical Properties of Fluids. I. Argon, Ethylene, Parahydrogen, Nitrogen, Nitrogen Trifluoride, and Oxygen**, *Journal of Physical and Chemical Reference Data*, 11(supplement 1), 1982 (rdb7959)

R-702p (para-hydrogen), R-728 (nitrogen), R-732 (oxygen), R-740 (argon), R-771 (nitrogen trifluoride), and R-1150 (ethene): thermodynamic properties; thermophysical data; equation of state (EOS), thermal conductivity, viscosity, and others

H-L. Zhang, H. Sato, and K. Watanabe (Keio University, Japan), **Second Virial Coefficients for R-32, R-125, R-134a, R-143a, R-152a, and Their Binary Mixtures**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:622-629, 1995 (8 pages with 6 figures and 2 tables, rdb-7907)

second virial coefficients and proposed correlations derived from Burnett measurements for R-32, R-125, R-134a, R-143a, and R-152a; second virial coefficients for R-32/134a; thermodynamic properties; thermophysical data

V. P. Zhelezny, Y. Chernyak, V. N. Anisimov, Y. V. Semenyuk, and P. V. Zhelezny, **Liquid-Vapor Equilibria and Thermodynamic Properties of HFC-32/125 and HFC-143a/125 Systems**, *Proceedings of the Fourth Asian Thermophysical Properties Conference* (Tokyo, Japan, 5-8 September 1995), 2:335-338, 1995 (4 pages, rdb6C20)

thermodynamic properties, thermophysical data, R-32/125 and R-125/143a (R-410 and R-507 series) blends

Dymel® Aerosol Propellants, product information bulletin (240881D), DuPont Fluorochemicals, Wilmington, DE, August 1995 (10 pages with 1 figure and 3 tables, RDB6210)

R-134a, R-152a, R-E170 (DME), applications, properties, environmental impacts, stability, solubility, safety, toxicity, flammability, compatibility

Thermophysical Properties of Alternative Refrigerants, proposed research project 861-WS, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, in planning (ASH0861)

This research project is sponsored by ASHRAE Technical Committee 3.1, *Refrigerants and Brines*.

Thermophysical Properties of Environmentally Acceptable Fluorocarbons - HFC-134a and HCFC-123, Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR] and Japan Flon Gas

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Association (JFGA), Tokyo, Japan, 1991 (304 pages with 83 figures and 99 tables, in both Japanese and English, RDB2235)

This comprehensive volume summarizes critical, thermodynamic, transport, physical, chemical, compatibility, and other data available on R-123 and R-134a. Included are tabular data and/or plots for solubility, refractive index, dielectric constant, dielectric strength, PVT properties and equations of state (EOS), enthalpy, entropy, isobaric and isochoric specific heat capacity, isentropic expansion exponent, speed of sound, surface tension, viscosity, kinematic viscosity, and thermal conductivity. Data on thermal and chemical stability are summarized, including weight and length changes with polypropylene, polystyrene, polyethylene, polyvinylchloride, polyamide, polyimide, chlorinated and chlorosulfonated polyethylene, nitrile butadiene rubber, Butyl™ rubber, fluorocarbon rubber, ethylene propylene diene terpolymer (EPDM), urethane rubber, and polychloroprene. Safety data, including toxicity and flammability, are summarized. The volume contains an extensive list of references as well as discussion of the ranges and differences among property sources identified. An introductory section outlines conversions among several metric systems, including SI, and inch-pound units. It also reviews the environmental concerns with chlorofluorocarbon (CFC) refrigerants.

Thermophysical Properties of Refrigerants 123 and 134a, proposed research project 655A-TRP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, in planning (ASH0655A)

This project is sponsored by ASHRAE Technical Committee 3.1, *Refrigerants and Brines*.

Thermophysical Properties of Refrigerants 125 and 141b, proposed research project 6558-TRP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, in planning (ASH0655B)

This project is sponsored by ASHRAE Technical Committee 3.1, *Refrigerants and Brines*.

Transport Properties of Suva® Refrigerants: Suva® Cold-MP (HFC-134a), Suva® Trans A/C (HFC-134a), and Suva® Centri-LP (HCFC-123), product information report ART-1 (H-43855-1), DuPont Chemicals, Wilmington, DE, September 1992 (24 pages with 18 figures, available from JMC as RDB3438)

This report provides plots and equations for estimation of the transport properties of R-123 and R-134a. Liquid viscosity, liquid thermal conductivity, saturated liquid heat capacity, vapor viscosity at atmospheric pressure, vapor thermal conductivity at atmospheric pressure, vapor heat capacity, and vapor heat capacity ratio (C_p/C_v) are addressed. Corresponding data art plotted for R-11 and R-12 for all but the vapor heat capacity data for comparison. The plots and equations are repeated in inch-pound (IP) and metric (SI) units. The equations are based on curve fits of measured data.

Transport Properties of Suva® Refrigerants: Suva® HP62, Suva® HP80, and Suva® HP81, product information report ART-18 (H-49740), DuPont Chemicals, Wilmington, DE, May 1993 (40 pages with 34 figures, RDB3C03)

This report provides plots and equations for estimation of transport properties for R-402A and R-402B. These refrigerants are zeotropic blends of R-125, R-290 (propane), and R-22, namely R-125/290/22 (60/2/38) and (38/2/60), respectively. The report also covers R-404A, a zeotropic blend of three hydrofluorocarbons (HFCs) - R-125, R-143a, and R-134a - namely R-125/143a/134a (44/52/4). Saturated liquid viscosity, thermal conductivity, and heat capacity; vapor viscosity at atmospheric pressure; vapor thermal conductivity at atmospheric and high pressure; vapor heat capacity; and vapor heat capacity ratio (C_p/C_v) are addressed. Most include curves for R-502 for comparison. The plots and equations are repeated in inch-pound (IP) and metric (SI) units. The equations are based on curve fits of measured data. DuPont's product names for R-402A, R-402B, and R-404A are Suva® HP80, Suva® HP81, and Suva® HP62, respectively.

Transport Properties of Suva® Refrigerants: Suva® MP39, Suva® MP52, and Suva® MP66, product information report ART-10 (H-45949), DuPont Chemicals, Wilmington, DE, January 1993 (32 pages with 24 figures, available from JMC as RDB-3440)

This report provides plots and equations for estimation of transport properties for R-401A, R-401B, and R-401C. These refrigerants are zeotropic blends of R-22, R-152a, and R-124, namely R-22/152a/124 (53/13/34), (61/11/28), and (33/15/52), respectively. Saturated liquid viscosity, thermal conductivity, and heat capacity; vapor viscosity at atmospheric pressure; vapor thermal conductivity at atmospheric pressure; vapor heat capacity; and vapor heat capacity ratio (C_p/C_v) are addressed. Plots provide correction factors for vapor viscosity at higher pressures for vapor densities to 110 kg/m^3 (7 lb/cf). The plots and equations are repeated in inch-pound (IP) and metric (SI) units. The equations are based on curve fits of measured data. DuPont's product names for R-401A, R-401B, and R-401C are Suva® MP39, Suva® MP66, and Suva® MP52, respectively.

MATERIALS COMPATIBILITY

T. Akiya, T. Shimazaki, M. Oowa (National Institute of Materials and Chemical Systems, Japan), M. Matsuo, and Y. Yoshida (Matsushita Electric Industrial Company, Limited, Japan), **Formation Conditions of Clathrates between HFC Alternative Refrigerants and Water,** *Preprints of the 13th Symposium on Thermophysical Properties* (Boulder, CO, 22-27 June 1997), 1997 (18 pages with 7 figures and 1 table, available from JMC as RDB8202)

examines conditions under which R-32, R-125, R-134a, R-407C, and R-410A combine with water to form clathrates: uses phase diagrams to determine the critical decomposition temperatures and pressures; concludes that clathrate compounds can form with water in the low-pressure side of air-conditioners and heat pumps at evaporating temperatures lower than approximately 14 °C (57 °F) for R-407C and 20°C (68 °F) for R-410A

F. Broesby **Chemical Reactions in Ammonia, Carbon Dioxide, and Hydrocarbon Systems,** *Proceedings of the IIR Conference on Applications for Natural Refrigerants* (Århus, Denmark, 3-6 September 1996), International Institute of Refrigeration (IIR), Paris, France, 14.1-14.6, September 1996 (5 pages, rdb9927)

compatibility with R-170 (ethane), R-290 (propane), R-600 (n-butane), R-600a (isobutane), R-717 (ammonia), and R-744 (carbon dioxide)

R. C. Cavestri and D. L. Schooley (Imagination Resources, Incorporated, IRI), **Compatibility of Manufacturing Process Fluids with R-134a and Polyolester Lubricant,** report DOE/CE/23810-55, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, July 1996 (32 pages with 12 tables, available from JMC as RDB6805)

This report identifies processing fluids known to be used in the manufacture of compressors and other components for air-conditioning and refrigeration equipment. The objective was to investigate whether these fluids contribute to formation of acids might corrode metals or other materials that may block capillary tubes, expansion valves, filters, and desiccants. 64 fluids were tested for compatibility with R-134a and a dried, pentaerythritol ester mixed acid lubricant (ICI Emkarate™ RL 32H), indicated as containing no additives. Solutions or suspensions of the process fluid residues in the polyolester (POE) lubricant were heated for 14 days at 175 °C (347 °F) in evacuated, sealed glass tubes containing polished valve steel (Sandvik) coupons. The report outlines the methods used to prepare the residues or solutions of the fluids. Miscibility tests were performed in a 90/10 mixture by weight of R-134a and the POE with the fluid residue contaminants, and then scanned in 10 °C (18 °F) increments from -40 °C (-40 °F) for signs of turbidity, haze formation, or oil separation. Their observation was deemed a sign of immiscibility. Tables report the visual condition of the POE, soluble iron, total acid number (TAN), and critical miscibility of the aged mixtures for uncured and uncured sealants and the other fluids. No interpretations or conclusions are given for the data presented. The brazing fluxes tested were Lucas-Milhaupt Incorporated *Handy Flux D*, J. W. Harris *Stay Silv White*, and Novamax *No Rez 65*. Machining coolants included Solene Industrial Lubricants *1000*, Cincinnati Milacron *Cimstar 3700T* and *40 Pink,* Castrol Industrial Central Incorporated *Safety Cool 800 / Syntilo 9954*, Chemtool *CT500*, Oakite *Controlant 127S* and *3000ss*, and Diversey-Dubois *Lubricoolant Tec*. The detergents, degreasers, and cleaners examined included Brulin Corporation *815GD* and *815QR*; Solvox Manufacturing Company *Special 474*; Florida Chemical Company *D-Limonene;* Oakite *Okemclean, Improclean 1300*, *Rustripper*, *LSD, 31*, and *77*; Parker-Amchem *Parco 142*; and Diversey-Dubois *Super Terj* and *ISW-29*. Iron phosphatizers included Oakite *Cryscoat 747*, *1127*, *2147*, and *Ultra Seal (Rinse).* Tested lubricants were Schrader-Bellows *F4422 Oil*, Castrol *Honilo 480*, Etna Products *Master Draw 566* and *1969A1*, Witco *Suniso 160* and *3GS*, Oakite *Formula 59*, Benz Pol Company *Rex Draw 176*, and Oak International *11-B* and *Oil 50-5*. Rust inhibitors and preventatives included Birchwood Casey *Dri-Touch IRP1*, Castrol *Rustilo DW924*, Research Metal Fluids *Resco Oxy Kleen 4926A*, *Koate Syn*, and *Ultra Koate XP*, Almco *2420*, Novamax *R44*, Diversey-Dubois *E-314* and *ICS-423*, Quaker Chemical *Ferracote 368*, Chemical Technologies *Protech 1300*, Chem Tool *CT625*, Oakite *Inpro-tect 600* and *670*, *Renovator,* and *Special Protective Oil*, Puma Technologies *Meca Lube,* and Met-Chem *211*. Tested sealants were Loctite *515*, *640*, and *RC 1620* as well as Oakite *Renovator.* Eight appendices tabulate the published compositions and working concentrations for these fluids.

R. C. Cavestri (Imagination Resources, Incorporated, IRI), **Compatibility of Refrigerants and Lubricants with Engineering Plastics**, report DOE/-CE/23810-15, Air-Conditioning and Refrigeration

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Technology Institute (ARTI), Arlington, VA, September 1993 with December 1993 revisions (182 pages with 7 figures and 106 tables, available from JMC as RDB4103; type on page 74 is small and may be difficult to read)

This report provides extensive compatibility information on 23 engineering plastics with 10 refrigerants, 7 lubricants, and 17 refrigerant-lubricant combinations. An introduction notes the complexities of both materials selection and application-specific influences, such as changes in environmental conditions and residual molding stresses. A narrative outlines the experimental methods used, including modifications to standard test procedures. Six figures depict the apparatus used in the different tests. The report then presents significant findings. 23 summaries provide generic and trade names for the plastics, the molecular structure if published, a description, and tabular findings for total acid number (TAN), tensile change, and elongation change. The report concludes that the refrigerants and lubricants seemed to have no dramatic effects on most of the plastics tested. Most absorbed some refrigerant and lubricant, which softened the plastics slightly. The most prominent observation was a decrease in tensile strength and elongation due to heating alone. Had this effect not been observed by control tests with air, the study would have concluded that all of the plastics tested were incompatible. In fact, only three (acrylonitrile – butadiene-styrene terpolymer, polyphenylene oxide, and polycarbonate) were affected severely enough to be considered incompatible with HFC refrigerants and lubricants. The report also notes that the analyses would have been clearer with prior annealing and dehydration; special attention is suggested for PET and PBT. Finally, the report notes that some form of extractable component can be obtained whenever any plastic is used with polar refrigerants and lubricants. The plastics included polyphthalamide (Amoco Amodel® AD-1000 HS), acrylonitrile-butadiene-styrene terpolymer (ABS, GE Cycolac® GPM 4700), acetal (DuPont Delrin® II 11500), phenolic (Hooker Durez®), polyvinylidene fluoride (Atochem Kynar® 720), polycarbonate (GE Lexan® 161), modified polyphenylene oxide (PPO, GE Noryl® 731), polypropylene (Himont Profax™ 6331 NW), polyarylsulfone (Amoco Radel® A-200), polyethylene terephthalate (PET, DuPont Rynite® 530), polyphenylene sulfide (PPS, GE Supec™ G401), polytetrafluoroethylene (PTFE, DuPont Teflon®), high strength polyamide-imide (PAI, Amoco Torlon® 4203L), 12% graphite polyamide-imide (PAI, Amoco Torlon® 4301), polyetherimide (PEI, GE Ultem® 1000), modified polyetherimide (PEI, GE Ultem® CRS 5001), polyaryletherketone (PAEK, BASF Ultrapek®), polybutylene terephthalate (PBT, GE Valox® 325 PBT), polyimide-DF (PI-DF, DuPont Vespel® DF), polyimide-DF-ISO (PI-DF-ISO, DuPont Vespel® DF-ISO), poly(aryl ether ether ketone) (PEEK, ICI Victrex™ PEEK 450 G), liquid crystal polymer (LCP, Amoco Xydar® MG450), and polyamide nylon 6/6 (DuPont Zytel® 101). The refrigerants tested included R-22, R-32, R-123, R-124, R-125, R-134, R-134a, R-142b, R-143a, and R-152a. The lubricants included a mineral oil (MO, BV Associates R0-15); an alkylbenzene (AB, Shrieve Zerol® 150); three polyalkylene glycols (PAGs), namely polypropylene glycol butyl monoether (ICI Emkarox® VG32), polypropylene glycol diol (Dow P-425), and a modified polyglycol (AlliedSignal BRL-150); and two polyolesters (POEs), namely pentaerythritol ester mixed acid (ICI Emkarate™ RL 22H, formerly RL 244), and pentaerythritol ester branched acid (Henkel Emery® 2927-A). Appendices provide further details. The first two list the commercial names of the products tested and summarize the molding specifications and conditions for the plastics. The next comprises seven tables that summarize the changes for immersions in the individual lubricants at 60 and 100 °C (140 and 212 °F). Observations of particulates, cracking, crazing, softening, and color change are presented. Quantitative data are provided for dimensional (length, width, and thickness) and weight changes. Ten tables then summarize corresponding changes following exposures to the refrigerants at room temperature and 60 °C (140 °F) for 14 days. 11 tables summarize the creep modulus of the plastics at 10-300 hours for immersions in air and the 10 refrigerants with POE branched acid. 36 tables summarize physical, tensile, and elongation changes following exposures to refrigerant-lubricant mixtures. The last three appendices document the TANs of thermally aged lubricants with and without plastics, tensile properties of plastics after lubricant immersions, and temperature and dehydrating effects on the plastics.

S. Corr, P. Dowdle, G. Tompsett, R. W. Yost, T. W. Dekleva (ICI Klea), J. Allison, and R. Brutsch (Von Roll Isola, Switzerland), **Compatibility of Non Metallic Motor Components with R-22 and R-502 Replacement Refrigerants,** seminar presentation (ASHRAE Winter Meeting, New Orleans, LA, 24 January 1994), ICI Klea, Wilmington, DE, January 1994 (32 pages with 32 presentation charts, available from JMC as RDB4216)

These presentation charts provide information on materials compatibility tests of insulation materials, tapes, resins, laminates, cable sheaths and ties, and plastics for motors for hermetic compressors with refrigerants and lubricants. The tests performed gauged changes in appearance, weight, volume, and hardness following autoclave tests at 130 °C (266 °F) for 14 days. The charts outline the test procedures, provide details (composition and application) of the materials tested, and present the findings. The tested materials included a composite of polyethylene terephthalate (PET) between two polyester felts impregnated with resin (Myoflex PVS), a composite of PET between two pieces of polyamide paper impregnated with resin (Myoflex N), glass fiber tape impregnated with epoxy varnish (Vetroflex 253.13), glass fiber tape impregnated with polyurethane varnish (Vetroflex 253.10), composite of mica paper and glass fabric impregnated with epoxy resin (Samicatherm 366.28), polyester fleece tape impregnated with pigments and flexible epoxy resin (Epoflex 215.01), composite of mica, glass threads, and polyester film with impregnated with acrylic (Filosam 326.52-11), composite of mica, glass threads, and polyester film with impregnated with epoxy (Filosam 326.52-30), composite of mica and glass fabric impregnated with polyester-amide (Samicatherm 366.58 with resin 3308), composite of mica and glass fabric and polyester film impregnated with polybutadiene resin (Isomica 326.04), and composite of mica and glass fabric and polycarbonate film impregnated with polybutadiene resin (Isomica 326.95-66) insulations. They also included unsaturated polyester-amide resin containing styrene as a thinner (resin 3316), solventless unsaturated polyester-amide resin (resin 3305), unsaturated polyester-amide resin without styrene (resin 3350), modified epoxy resin with little solvent (resin 3405), and modified unsaturated polyester-amide without styrene (resin 3360) winding resins. They also included modified cross-linked polyolefin (Exar-500) and diacetate fibers, PET film, and polyamide paper coated with polyester/polyurethane (2MN-180) lead wires; silicone rubber and synthetic yarn braid impregnated with polyurethane (Siwo-Kul) cable; stabilized rayon impregnated with resin (RT8) tying tape; impregnated polyester braid (Siligaine) cable sleeving; polyester nonwoven fleece impregnated with carbon particles conductive tape; polyester fabric impregnated with silicone carbide and epoxy resin semiconductive tape; woven glass cloth laminated with epoxy resin (G11) dielectric laminate; and woven glass cloth laminated with polyester resin (GP03) laminate for terminal boards. They also included THEIC modified polyester (Thermex 180 PZ/2), polyester-amide coated with polyamide-amide (Thermex 200 PZ/2), two modified polyester-amide (Thermex 305-1 and 305-2), modified polyester-amide coated with polyamide-amide (Thermex 306), two self bonding, modified polyamide-amide (Thermibond 158 and 164) enameled motor winding wires; hard phenolic resin (Varnih 2004 HFP), modified alkyd polyester resin (Varnih 2005 HFP), and modified polyester-amide resin (Varnih 2053 HFP) winding varnishes; glass filament fused with synthetic yarn (Daglas) for use with enameled wire; polytetrafluoroethylene (PTFE) for gaskets, seals, and insulation; polyamide (nylon 6,6) molding material; and polybutyl terephthalate (PBT) for electrical terminal blocks. These 40 materials were tested with neat R-22, R-32, R-134a, and R-32/134a (30/70); R-22 with mineral oil (MO, Witco Suniso® 3GS); R-32 and R-32/134a with two ester lubricants (ICI Emkarate™ 68S and 32S); and R-22 with an ester (ICI Emkarate™ 32S). Eight tables present subjective observations ("ok" or "x") after exposures. 16 figures then show the weight, volume, and hardness changes as percentages. A final chart present three conclusions: 1) the materials generally performed as well or better in the hydrofluorocarbon (HFC)/ester exposures than in R-22/MO, 2) HFCs and esters appear compatible with many motor materials, and 3) accelerated thermal aging can be harsher than actual application.

S. Corr, T. W. Dekleva, P. Dowdle, G. Tompsett (ICI Klea), J. Allison, and R. Brutsch (Von Roll Isola, Switzerland), **Compatibility of Non-Metallic Motor Components With R22 and R502 Replacement Refrigerants,** *Proceedings: Electrical Electronics Insulation Conference and Electrical Manufacturing and Coil Winding Conference* (EEIC/ICWA), Rosemont, IL, 507-512, October 1993 (6 pages with 20 figures and 3 tables, RDB3A24)

This paper presents materials compatibility data for motor insulation materials with hydrofluorocarbon (HFC) refrigerants R-32, R-125, and R-134a and a neopentyl polyolester lubricant (ICI Emkarate™, a mixed acid pentaerythritol ester). An introduction and table explain the need for HFCs to replace R-22 and R-502 and the associated need to change lubricants from traditional mineral oils. The tests performed gauged changes in appearance, volume, hardness, and weight following autoclave tests at 130 °C (266 °F) for 14 days at autogenous pressures; moisture content also was determined prior to the tests. The paper outlines the test procedures, provides details (composition and application) on the materials tested, and present the findings. The tested materials included a composite of polyethylene terephthalate (PET) between two polyester felts impregnated with resin (Myoflex PVS), a composite of PET between two pieces of polyamide paper impregnated with resin (Myoflex N), glass fiber tape impregnated with epoxy varnish (Vetroflex 253.13), glass fiber tape impregnated with polyurethane varnish

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(Vetroflex 253.10), composite of mica paper and glass fabric impregnated with epoxy resin (Samicatherm 366.28), polyester fleece tape impregnated with pigments and flexible epoxy resin (Epoflex 215.01), composite of mica, glass threads, and polyester film with impregnated with acrylic (Filosam 326.52-11), composite of mica, glass threads, and polyester film with impregnated with epoxy (Filosam 326.52-30), composite of mica and glass fabric impregnated with polyester-imide (Samicatherm 366.58 with resin 3308), composite of mica and glass fabric and polyester film impregnated with polybutadiene resin (Isomica 326.04), and composite of mica and glass fabric and polycarbonate film impregnated with polybutadiene resin (Isomica 326.95-66) insulations. They also included unsaturated polyester-imide resin containing styrene as a thinner (resin 3316), solventless unsaturated polyester-imide resin (resin 3305), unsaturated polyester-imide resin without styrene (resin 3350), modified epoxy resin with little solvent (resin 3405), and modified unsaturated polyester-imide without styrene (resin 3360) winding resins. They also included modified cross-linked polyolefin (Exar-500) and diacetate fibers, PET film, and polyamide paper coated with polyester/polyurethane (2MN-180) lead wires; silicone rubber and synthetic yarn braid impregnated with polyurethane (Siwo-Kul) cable; stabilized rayon impregnated with resin (RT8) tying tape; impregnated polyester braid (Siligaine) cable sleeving; polyester nonwoven fleece impregnated with carbon particles conductive tape; polyester fabric impregnated with silicone carbide and epoxy resin semiconductive tape; woven glass cloth laminated with epoxy resin (G11) dielectric laminate; and woven glass cloth laminated with polyester resin (GP03) laminate for terminal boards. They also included theic modified polyester (Thermex 180 PZ/2), polyester-imide coated with polyamide-imide (Thermex 200 PZ/2), two modified polyester-imide (Thermex 305-1 and 305-2), modified polyester-imide coated with polyamide-imide (Thermex 306), two self bonding, modified polyamide-imide (Thermibond 158 and 164) enameled motor winding wires; hard phenolic resin (Varnih 2004 HFP), modified alkyd polyester resin (Varnih 2005 HFP), and modified polyester-imide resin (Varnih 2053 HFP) winding varnishes; glass filament fused with synthetic yarn (Daglas) for use with enameled wire; polytetrafluoroethylene (PTFE) for gaskets, seals, and insulation; polyamide (nylon 6,6) molding material; and polybutyl terephthalate (PBT) for electrical terminal blocks. These 40 materials were tested with neat R-22, R-32, R-134a, and R-32/134a (30/70); R-22 with mineral oil (MO, Witco Suniso® 3GS); R-32 and R-32/134a with two ester lubricants (ICI Emkarate™ 68S and 32S); and R-22 with two same esters. A tables presents subjective observations ("ok" or "x") after exposures. 20 figures then show the hardness, volume, weight changes as percentages. The paper concludes that the materials appeared to perform as well or better in the HFC and HFC/ester exposures as in R-22 and R-22 with MO. Incomplete data for R-125 and R-125 with ester suggests comparable behavior to that with R-32 and R-134a. The paper comments further on the harshness of the tests and resulting impacts on resins and cables.

R. G. Doerr and T. D. Waite (The Trane Company), **Compatibility of Refrigerants and Lubricants with Motor Materials Under Retrofit Conditions**, report DOE/CE/23810-63 volume I, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, October 1996 (200 pages with 114 tables, available from JMC as RDB6C07)

This report presents the findings of retrofit compatibility tests on materials used in motors for hermetic compressors, with refrigerants and lubricants. These materials were tested in accordance with UL Standard 2171, by exposures first to "original" refrigerant-oil mixtures and then to alternative refrigerant-lubricants mixtures. The sequential, 500-hour exposures simulate the effects of retrofit. Some samples were exposed to the original refrigerant-oil mixture for a total of 1000 hours, as a control. The report identifies the materials used, test procedures, sample preparation, and results. The original and retrofit combinations were R-11/paraffinic mineral oil (MO, Penreco Sontex 300LT) and R-123/MO (Penreco Sontex 300LT), R-11/MO (Penreco Sontex 300LT) and R-245ca/polyolester (POE, CPI® Solest® 68), R-12/naphthenic MO (Witco Suniso® 3GS) and R-134a/POE (CPI® Solest® 68), R-22/MO (Suniso® 3GS) and R-407C/POE mixed acids (ICI Emkarate™ RL 32H), R-123/mineral oil (Penreco Sontex 300LT) and R-245ca/POE (CPI® Solest® 68), and R-502/MO (Suniso® 3GS) and R-404A/POE branched acid (Castrol Icematic® SW32). The low-pressure refrigerants (involving R-11, R-123, and R-245ca were tested at 100 °C (212 °F), and the high-pressure refrigerants were tested at 127 °C (260 °F). The magnet wire insulations tested were a modified polyester base overcoated with polyamide imide (Phelps Dodge Armored Poly-Thermaleze 2000), a polyester imide overcoated with polyamide-imide (Phelps Dodge / Schenectady Chemical), and a modified polyester base overcoated with polyamide imide and epoxy saturated glass (Phelps Dodge Armored Poly-Thermaleze Daglass 2000). They were tested for dielectric breakdown and burnout strength. The varnishes included a water-base epoxy phenolic (Schenectady Isopoxy® 800), a solvent epoxy phenolic (P. D.

George 923), and a solvent epoxy (Sterling® U-475 EH). Coated helical coils tested for bond strength. The sheet insulations tested were a polyethylene terephthalate film (DuPont Mylar® 900 MO), a low oligomer PET film (ICI Melinex® 228), a PET composite (Westinghouse Dacron-Mylar-Dacron®, DMD), an aramid fiber mat (DuPont Nomex® 410 10 mil), an aramid fiber mica mat (DuPont Nomex® Mica 418), and a composite of aramid mat and PET film (Westinghouse Nomex-Mylar-Nomex®, NMN). These insulation sheets were tested for tensile strength, elongation, and dielectric breakdown. The spiral-wrapped sleeving materials tested were a PET film (Insulations Sales Mylar®) and a composite of aramid mat and polyester film (Insulations Sales Nomex-Mylar®). The lead wires tested were a polyester composite (A. O. Smith DMD) and a polyester, fluoropolymer composite (A. O. Smith Dacron-Teflon-Mylar-Dacron®, DMTD). The sleeving and lead wires were tested for dielectric breakdown. Other materials tested were a polyester tie cord (Ludlow Textiles); braided polyester, acrylic binder assembly tape; and polyester mat assembly tape. They were tested for tensile strength and elongation. Assembled motorettes with the three wire types were tested for their ability to withstand applied voltages. In addition, all materials were inspected visually. The tests performed found the exposed materials to be compatible with the refrigerants and lubricants tested with exception of delamination and blistering of the Nomex sheet insulation, especially after removal of absorbed refrigerant. This effect was attributed to solution of the adhesive used. PET embrittlement was observed, but found to be due to moisture and not the refrigerants and lubricants. The nitrile tested was deemed incompatible with R-123 and the neoprene with R-245ca.

R. G. Doerr and T. D. Waite (The Trane Company), **Compatibility of Refrigerants and Lubricants with Motor Materials Under Retrofit Conditions,** report DOE/CE/23810-63 volume II, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, October 1996 (264 pages essentially all tables, available from JMC as RDB6C08)

This report presents the measured data for high-pressure refrigerants from retrofit compatibility tests of R-134a for R-12, R-407C for R-22, and R-404A for R-502 on materials used in motors, for hermetic compressors. The original and retrofit combinations were R-12/naphthenic mineral oil (MO, Witco Suniso® 3GS) and R-134a/polyol-ester (POE, CPI® Solest® 68), R-22/MO (Suniso® 3GS) and R-407C/POE mixed acids (ICI Emkarate™ RL 32H), and R-502/MO (Suniso® 3GS) and R-404A/POE branched acid (Castrol Icematic® SW32). The magnet wire insulations tested were a modified polyester base overcoated with polyamide imide (Phelps Dodge Armored Poly-Thermaleze 2000), a polyester imide overcoated with polyamide-imide (Phelps Dodge / Schenectady Chemical), and a modified polyester base overcoated with polyamide imide and epoxy saturated glass (Phelps Dodge Armored Poly-Thermaleze Daglass 2000). They were tested for dielectric breakdown and burnout strength. The varnishes included a water-base epoxy phenolic (Schenectady Isopoxy® 800), a solvent epoxy phenolic (P. D. George 923), and a solvent epoxy (Sterling® U-475 EH). Coated helical coils tested for bond strength. The sheet insulations tested were a polyethylene terephthalate film (DuPont Mylar® 900 MO), a low oligomer PET film (ICI Melinex® 228), a PET composite (Westinghouse Dacron-Mylar-Dacron®, DMD), an aramid fiber mat (DuPont Nomex® 410 10 mil), an aramid fiber mica mat (DuPont Nomex® Mica 418), and a composite of aramid mat and PET film (Westinghouse Nomex-MylarNomex®, NMN). These insulation sheets were tested for tensile strength, elongation, and dielectric breakdown. The spiral-wrapped sleeving materials tested were a PET film (Insulations Sales Mylar®) and a composite of aramid mat and polyester film (Insulations Sales Nomex-Mylar®). The lead wires tested were a polyester composite (A. O. Smith DMD) and a polyester, fluoropolymer composite (A. O. Smith Dacron-Teflon-Mylar-Dacron®, DMTD). The sleeving and lead wires were tested for dielectric breakdown. Other materials tested were a polyester tie cord (Ludlow Textiles); braided polyester, acrylic binder assembly tape; and polyester mat assembly tape. They were tested for tensile strength and elongation. Assembled motorettes with the three wire types were tested for their ability to withstand applied voltages. In addition, all materials were inspected visually. See RDB6C07 for discussion of the test methods and conclusions.

R. G. Doerr and T. D. Waite (The Trane Company), **Compatibility of Refrigerants and Lubricants with Motor Materials Under Retrofit Conditions**, report DOE/CE/23810-63 volume III, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, October 1996 (168 pages essentially all tables, available from JMC as RDB6C09)

This report presents the measured data for high-pressure refrigerants from retrofit compatibility tests of R-123 for R-11, R-245ca for R-11, and R-245ca for R-123 on materials used in motors, for hermetic compressors. The original and retrofit combinations were R-11/paraffinic mineral oil (MO, Penreco Sontex 300LT) and R-123/MO (Penreco Sontex 300LT), R-11/MO (Penreco

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Sontex 300LT), and R-245ca/polyolester (POE, CPI® Solest® 68), and R-123/mineral oil (Penreco Sontex 300LT) and R-245ca/POE (CPI® Solest® 68). The magnet wire insulations tested were a modified polyester base overcoated with polyamide imide (Phelps Dodge Armored Poly-Thermaleze 2000), a polyester imide overcoated with polyamide-imide (Phelps Dodge / Schenectady Chemical), and a modified polyester base overcoated with polyamide imide and epoxy saturated glass (Phelps Dodge Armored Poly-Thermaleze Daglass 2000). They were tested for dielectric breakdown and burnout strength. The varnishes included a water-base epoxy phenolic (Schenectady Isopoxy® 800), a solvent epoxy phenolic (P. D. George 923), and a solvent epoxy (Sterling® U-475 EH). Coated helical coils tested for bond strength. The sheet insulations tested were a polyethylene terephthalate film (DuPont Mylar® 900 MO), a low oligomer PET film (ICI Melinex® 228), a PET composite (Westinghouse Dacron-Mylar-Dacron®, DMD), an aramid fiber mat (DuPont Nomex® 410 10 mil), an aramid fiber mica mat (DuPont Nomex® Mica 418), and a composite of aramid mat and PET film (Westinghouse Nomex-Mylar-Nomex®, NMN). These insulation sheets were tested for tensile strength, elongation, and dielectric breakdown. The spiral-wrapped sleeving materials tested were a PET film (Insulations Sales Mylar®) and a composite of aramid mat and polyester film (Insulations Sales Nomex-Mylar®). The lead wires tested were a polyester composite (A. O. Smith DMD) and a polyester, fluoropolymer composite (A. O. Smith Dacron-Teflon-Mylar-Dacron®, DMTD). The sleeving and lead wires were tested for dielectric breakdown. Other materials tested were a polyester tie cord (Ludlow Textiles); braided polyester, acrylic binder assembly tape; and polyester mat assembly tape. They were tested for tensile strength and elongation. Assembled motorettes with the three wire types were tested for their ability to withstand applied voltages. In addition, all materials were inspected visually. See RDB6C07 for discussion of the test methods and conclusions.

R. G. Doerr and T. D. Waite (The Trane Company), **Compatibility of Refrigerants and Lubricants with Motor Materials Under Retrofit Conditions**, report DOE/CE/23810-63 volume IV, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, October 1996 (52 pages with 90 photographs and 3 tables, available from JMC as RDB6C10; color copies available for $52 additional)

This report presents photographic records of retrofit compatibility tests on materials used in motors, for hermetic compressors, with refrigerants and lubricants. The original and retrofit combinations were R-11/paraffinic mineral oil (MO, Penreco Sontex 300LT) and R-123/MO (Penreco Sontex 300LT), R-11/MO (Penreco Sontex 300LT) and R-245ca/polyolester (POE, CPI® Solest® 68), R-12/naphthenic MO (Witco Suniso® 3GS) and R-134a/POE (CPI® Solest® 68), R-22/MO (Suniso® 3GS) and R-407C/POE mixed acids (ICI Emkarate™ RL 32H), R-123/mineral oil (Penreco Sontex 300LT) and R-245ca/POE (CPI® Solest® 68), and R-502/MO (Suniso® 3GS) and R-404A/POE branched acid (Castrol Icematic® SW32). The low-pressure refrigerants (involving R-11, R-123, and R-245ca were tested at 100 °C (212 °F), and the high-pressure refrigerants were tested at 127 °C (260 °F). The magnet wire insulations tested were a modified polyester base overcoated with polyamide imide (Phelps Dodge Armored Poly-Thermaleze 2000), a polyester imide overcoated with polyamide-imide (Phelps Dodge / Schenectady Chemical), and a modified polyester base overcoated with polyamide imide and epoxy saturated glass (Phelps Dodge Armored Poly-Thermaleze Daglass 2000). They were tested for dielectric breakdown and burnout strength. The varnishes included a water-base epoxy phenolic (Schenectady Isopoxy® 800), a solvent epoxy phenolic (P. D. George 923), and a solvent epoxy (Sterling® U-475 EH). Coated helical coils tested for bond strength. The sheet insulations tested were a polyethylene terephthalate film (DuPont Mylar® 900 MO), a low oligomer PET film (ICI Melinex® 228), a PET composite (Westinghouse Dacron-Mylar-Dacron®, DMD), an aramid fiber mat (DuPont Nomex® 410 10 mil), an aramid fiber mica mat (DuPont Nomex® Mica 418), and a composite of aramid mat and PET film (Westinghouse Nomex-Mylar-Nomex®, NMN). These insulation sheets were tested for tensile strength, elongation, and dielectric breakdown. The spiral-wrapped sleeving materials tested were a PET film (Insulations Sales Mylar®) and a composite of aramid mat and polyester film (Insulations Sales Nomex-Mylar®). The lead wires tested were a polyester composite (A. O. Smith DMD) and a polyester, fluoropolymer composite (A. O. Smith Dacron-Teflon-Mylar-Dacron®, DMTD). The sleeving and lead wires were tested for dielectric breakdown. Other materials tested were a polyester tie cord (Ludlow Textiles); braided polyester, acrylic binder assembly tape; and polyester mat assembly tape. They were tested for tensile strength and elongation. Assembled motorettes with the three wire types were tested for their ability to withstand applied voltages. In addition, all materials were inspected visually. See RDB6C07 for discussion of the test methods and conclusions.

R. G. Doerr and T. D. Waite (The Trane Company), **Compatibility of Refrigerants and Lubricants with Electrical Sheet Insulation Under Retrofit Conditions,** *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 175-180, July 1996; republished as report DOE/CE/23810-72B, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 1996 (10 pages with 2 tables, available from JMC as RDB6836)

This paper summarizes tests conducted on six electrical sheet materials used in hermetic motors for refrigeration compressors, to determine whether prior exposure to an original refrigerant and mineral oil would affect compatibility with an alternative refrigerant and lubricant after retrofit. The materials were exposed first to the original refrigerant and lubricant and then to the alternatives, for 500 hours at elevated temperature for each refrigerant-lubricant system. R-11, R-12, R-22, and R-502 were tested as original refrigerants; R-123, R-134a, R-245ca, R-404A, and R-407C were tested as retrofit alternatives, the last four with polyolester (POE) lubricants. The test materials included a standard polyester film (DuPont Mylar® 900 MO), a low oligomer polyester film (ICI Melinex® 228), a polyester composite (Westinghouse Dacron-Mylar-Dacron®), an aramid fiber mat (DuPont Nomex® 410 10 mil), an aramid fiber mica mat (DuPont Nomex® Mica 418), and an aramid mat, polyester film composite (Westinghouse Nomex-Mylar-Nomex®). These insulation sheets were tested for tensile strength, elongation, and dielectric breakdown. The paper outlines the test methods and materials, provides a qualitative table of findings, and discusses the specific observations for each material tested. It concludes that the tested materials appeared to be as compatible with the alternatives as with the original refrigerants and lubricants. One exceptions was sheet insulation containing the aramid fibre mat, which showed delamination and blistering particularly after removal of absorbed refrigerant at high temperature. A second was polyethylene terephthalate (PET), which became embrittled. Subsequent tests, under extremely dry conditions, showed that embrittlement of the PET materials could be attributed to moisture present during the exposure.

R. G. Doerr and T. D. Waite (The Trane Company), **Compatibility of R-245ca with Motor Materials Under Retrofit Conditions**, presentation (ASHRAE Annual Meeting, San Diego, CA, 24-28 June 1995), report DOE/CE/23810-62A, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 28 June 1995 (4 pages with 20 presentation charts including 9 tables, available from JMC as RDB5802)

A series of presentation charts briefly outlines interest in R-245ca as a candidate to replace R-11 and R-123. It then relates the present compatibility study to prior, published work by the authors that used the same approach. The charts describe exposures of materials to R-11 or R-123 with mineral oil followed by R-245ca and an unidentified, polyolester lubricant. Data are tabulated for varnishes, magnet wire, sheet insulation, and nitrile and neoprene elastomers. The charts note that most materials appear compatible with R-245ca under retrofit conditions. Concerns are noted with aramid-polyethylene terephthalate (PET)-aramid sheet insulation due to blistering and to shrinkage of neoprene. The final chart notes that the flammability, toxicity, efficiency, and cost of R-245ca and/or blends containing it are unresolved.

R. G. Doerr and S. A. Kujak (The Trane Company), **Compatibility of Refrigerants and Lubricants with Motor Materials,** *ASHRAE Journal,* 35(8):4247, August 1993 (6 pages with 3 tables, RDB3A04)

This article summarizes a detailed investigation (see RDB3857) of the effects of 11 refrigerants and 17 refrigerant-lubricant combinations on 24 insulating materials for hermetic compressor motors. The introduction identifies absorption, extraction, and/or chemical dissolution as the primary deterioration mechanisms. It notes that absorption may change the dielectric strength or physical integrity or cause excessive swelling, softening, or decreased strength. Rapid desorption may cause blisters, crazing, surface craters, delamination, or bubbles within the insulating materials. Extraction of materials may result in a range of effects from embrittlement to complete dissolution. Extraction and dissolution, in turn, may cause other components to stick or lead to clogging of passage such as capillary tubes. Three tables classify motor materials as *compatible*, indicating a *concern,* or *incompatible* with pure refrigerants or refrigerant/lubricant mixtures. The effects of the pure refrigerants generally were greater than in combination with lubricants. The article notes that absorption of R-123 was higher than for other refrigerants by most motor materials. However, absorption of R-22, R-32, R-134, and R-152a followed by desorption, at higher temperatures, resulted in greater damage. These results suggest that high internal pressures and the desorption rate are as important as the amount of refrigerant absorbed. These changes decreased bond strength by as much as 95%, dielectric strength by as much as 70%, and decreased the physical integrity of the materials.

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Magnet wire with polyester-glass serving showed the highest burnout resistance and was influenced less by the refrigerants. Of the refrigerants tested, R-22 produced the greatest effects on the motor materials. Because R-22 has an excellent reliability history with many of them, the article concludes that the alternative refrigerants tested are expected to be compatible with most materials. The refrigerants tested included R-22, R-32, R-123, R-124, R-125, R-134, R-134a, R-142b, R-143a, R-152a, and R-245ca. The lubricants included naphthenic mineral oil (Witco Suniso® 3GS), alkylbenzene (Shrieve Zerol® 150), polyolester (POE) mixed acid (ICI Emkarate™ RL 22H, formerly RL 244), POE branched acid (Henkel Emery® 2927), a polyalkylene glycol (PAG) butyl monoether (ICI Emkarox® VG32), PAG modified with a fluoroalkyl group (AlliedSignal BRL-150), and a PAG diol (Dow Chemical P425). The varnishes included two solvent epoxies (P. D. George Sterling® U-475 EH and 923), a solvent epoxy phenolic (Sterling® Y-390 PG), 93% solids epoxy (Sterling® ER-610), and 100% solids VPI epoxy (Sterling® Y-833), and water-borne epoxy (Schenectady Isopoxy® 800). The magnet wires included a modified polyester base overcoated with polyamide imide (Phelps Dodge Armored Poly-Thermaleze 2000), a modified polyester base overcoated with polyamide imide and epoxy saturated glass (Phelps Dodge Armored Poly-Thermaleze Daglass 2000), and polyester imide overcoated with polyamideimide (Phelps Dodge / Schenectady Chemical). The sheet insulations tested were Westinghouse Nomex-Mylar-Nomex®, Westinghouse Dacron-Mylar-Dacron®, DuPont Mylar® 900 MO, DuPont Nomex® 410, DuPont Nomex® Mica 418, and ICI Melinex® 228. The spiral-wrapped sheet insulations tested were Insulations Sales Nomex®, Mylar®, and Nomex-Mylar®. The lead wires tested were A. O. Smith Dacron-Mylar-Dacron® and Dacron-Teflon-Dacron®. Other materials tested were woven glass tape (Carolina Narrow Heat Cleaned Fiberglass), heat shrinkable braided polyester tape (Electrolock), and glass-acrylic tape (Essex Permacel P247), and polyester tie cord (Ludlow Textiles).

R. G. Doerr and S. A. Kujak (The Trane Company), **Compatibility of Refrigerants and Lubricants with Motor Materials**, report DOE/CE/23810-13 volume I, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, May 1993 (166 pages with 118 tables, available from JMC as RDB3857)

This report presents very detailed compatibility information for 24 materials used in hermetic compressor motors with 11 refrigerants and 17 refrigerant-lubricant combinations. Volume I outlines the project, documents the test procedures, identifies the materials tested, discusses the findings, and provides both compatibility charts (*yes*, *concern, incompatible)* and summary tables of measured results. Companion volumes (see RDB3858 and RDB3859) supply the recorded data (approximately 40,000 measurements) for the exposures, and an unpublished volume contains photographs of the motor materials after exposures. The report concludes that the alternative refrigerants tested are expected to be compatible with most materials. This finding is based on comparisons to R-22, which produced the greatest effects on motor materials, but has an excellent reliability history with many of them. The report notes that absorption of R-123 by most motor materials was higher than for other refrigerants. However, absorption of R-22, R-32, R-134, and R-152a followed by desorption, at higher temperatures, resulted in greater damage. These results suggest that high internal pressures and the desorption rate are as important as the amount of refrigerant absorbed. Desorption caused blisters, cracks, internal bubbles, and delamination in some materials. These changes decreased bond strength by as much as 95%, dielectric strength by as much as 70%, and decreased the physical integrity of the materials. Magnet wire with polyester-glass serving showed the highest burnout resistance and was influenced less by the refrigerants. The refrigerant-lubricant combinations generally had less effect on the motor materials than the pure refrigerants. The refrigerants tested included R-22, R-32, R-123, R-124, R-125, R-134, R-134a, R-142b, R-143a, R-152a, and R-245ca. The lubricants included mineral oil (Witco Suniso® 3GS), alkylbenzene (Shrieve Zerol® 150), polyolester (POE) mixed acid (ICI Emkarate™ RL 22H, formerly RL 244), POE branched acid (Henkel Emery® 2927), a polyalkylene glycol (PAG) butyl monoether (ICI Emkarox® VG32), modified PAG (AlliedSignal BRL-150), and a PAG diol (Dow Chemical P425). The varnishes included two solvent epoxies (P. D. George Sterling® U-475 EH and 923), a solvent epoxy phenolic (Sterling® Y-390 PG), 93% solids epoxy (Sterling® ER-610), and 100% solids VPI epoxy (Sterling® Y-833), and water-borne epoxy (Schenectady Isopoxy® 800). The magnet wires included a modified polyester base overcoated with polyamide imide (Phelps Dodge Armored Poly-Thermaleze 2000), a modified polyester base overcoated with polyamide imide and epoxy saturated glass (Phelps Dodge Armored Poly-Thermaleze Daglass 2000), and polyester imide overcoated with polyamideimide (Phelps Dodge / Schenectady Chemical). The sheet insulations tested were Westinghouse Nomex-Mylar-Nomex®, Westinghouse Dacron-Mylar-Dacron®, DuPont Mylar® 900 MO, Du-

Pont Nomex® 410, DuPont Nomex® Mica 418, and ICI Melinex® 228. The spiral-wrapped sheet insulations tested were Insulations Sales Nomex®, Mylar®, and Nomex-Mylar®. The lead wires tested were A. O. Smith Dacron-Mylar-Dacron® and Dacron-Teflon-Dacron®. Other materials tested were woven glass tape (Carolina Narrow Heat Cleaned Fiberglass), heat shrinkable braided polyester tape (Electrolock), and glass-acrylic tape (Essex Permacel P247), and polyester tie cord (Ludlow Textiles).

R. G. Doerr and S. A. Kujak (The Trane Company), **Compatibility of Refrigerants and Lubricants with Motor Materials - Effects of Refrigerant Exposures on Motor Materials**, report DOE/CE/-23810-13 volume II, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, May 1993 (270 pages with 234 tables, available from JMC as RDB3858)

This report provides detailed compatibility information for 24 materials used in hermetic compressor motors with 11 refrigerants and 17 refrigerant-lubricant combinations. Volume II contains the recorded measurements before exposures, after exposures to the pure refrigerants, and before and after a subsequent 24-hour bake out, at 150 °C (302 °F), to remove absorbed refrigerant. The refrigerants tested included R-22, R-32, R-123, R-124, R-125, R-134, R-134a, R-142b, R-143a, R-152a, and R-245ca. All exposures were at 90 °C (194 °F) except for R-32 and R-125 at 60 °C (140 °F) and R-245ca at 121 °C (250 °F). The effects of heat alone were gauged by similar exposure to nitrogen (R-728) at both 60 and 90 °C (140 and 194 °F). The data are organized into 13 appendices for nitrogen at each exposure temperature and for each refrigerant. Each appendix contains 18 detailed tables providing measurements before and after exposures and before and after bake out; visual observations also are indicated. Triplicate measurements, except for weights, and average results are indicated for each test. Bond strength is compared to unexposed values for dipped coats of each of six varnishes on each of three magnet wires. The magnet wires included a modified polyester base overcoated with polyamide imide (Phelps Dodge Armored Poly-Thermaleze 2000), a modified polyester base overcoated with polyamide-imide and epoxy saturated glass (Phelps Dodge Armored Poly-Thermaleze Daglass 2000), and polyester-imide overcoated with polyamide-imide (Phelps Dodge / Schenectady Chemical). The varnishes included two solvent epoxies (P. D. George Sterling® U-475 EH and 923), a solvent epoxy phenolic (Sterling® Y-390 PG), 93% solids epoxy (Sterling® ER-610), and 100% solids VPI epoxy (Sterling® Y-833), and water-borne epoxy (Schenectady Isopoxy® 800). Burnout resistance and dielectric strength are compared to unexposed values for each varnish on each of the magnet wires and also to unvarnished specimens. Weight change is reported for exposed disks of the varnishes. Weight, tensile strength, elongation, and dielectric strength are compared to unexposed values for six sheet insulations (Westinghouse Nomex-Mylar-Nomex®, Westinghouse Dacron-Mylar-Dacron®, DuPont Mylar® MO, DuPont Nomex® 410, DuPont Nomex® Mica 418, and ICI Melinex® 228). Weight change is tabulated for Insulations Sales Nomex®, Mylar®, and Nomex-Mylar® spiral-wrapped sleeving insulation. Changes in weight and dielectric strength are presented for A. O. Smith Dacron-Mylar-Dacron® and Dacron-Teflon-Dacron® lead wire insulations. Weight and breaking load changes are supplied for woven glass tape (Carolina Narrow), heat shrinkable braided polyester tape (Electrolock), glass-acrylic tape (Essex Permacel P247), and polyester tie cord (Ludlow Textiles). [see RDB3857 for a summary and RDB3859 for data on exposures to the refrigerant-lubricant combinations]

R. G. Doerr and S. A. Kujak (The Trane Company), **Compatibility of Refrigerants and Lubricants with Motor Materials**, report DOE/CE/23810-13 volume III, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, May 1993 (370 pages with 324 tables, available from JMC as RDB3859)

This report provides detailed compatibility information for 24 materials used in hermetic compressor motors with 11 refrigerants and 17 refrigerant-lubricant combinations. Volume III contains the recorded measurements before exposures, after exposures to the refrigerant-lubricant mixtures, and before and after a subsequent 24-hour bake out at 150 °C (302 °F), to remove absorbed refrigerant. The measurements are tabulated for exposures at 127 °C (260 °F) to 17 refrigerant-lubricant combinations. R-22 was tested with mineral oil (Witco Suniso® 3GS). R-124, R-142b, and R-152a were tested with alkylbenzene (Shrieve Zerol® 150). R-134a was tested with a polyolester (POE) mixed acid (ICI Emkarate™ RL 22H, formerly RL 244); and R-32, R-125, R-134, R-134a, R-143a, and R-245ca with a POE branched acid (Henkel Emery® 2927 ISO 32). R-32, R-125, and R-134a were tested with a polyalkylene glycol (PAG) butyl monoether (ICI Emkarox® VG32); R-125 and R-134a with a modified PAG (AlliedSignal BRL-150); and R-134a with a PAG diol (Dow Chemical P425). The effects of heat alone were gauged by similar exposure to nitrogen (R-728). The data are or-

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ganized into 18 appendices, covering nitrogen and for each refrigerant. Each appendix contains 18 detailed tables providing measurements before and after exposures and before and after bake out; visual observations also are indicated. Triplicate measurements, except for weights, and average results are indicated for each test. Bond strength is compared to unexposed values for dipped coats of each of six varnishes on each of three magnet wires. The magnet wires included a modified polyester base overcoated with polyamide imide (Phelps Dodge Armored Poly-Thermaleze 2000), a modified polyester base overcoated with polyamide-imide and epoxy saturated glass (Phelps Dodge Armored Poly-Thermaleze Daglass 2000), and polyester-imide overcoated with polyamide-imide (Phelps Dodge / Schenectady Chemical). The varnishes included two solvent epoxies (P. D. George Sterling® U-475 EH and 923), a solvent epoxy phenolic (Sterling® Y-390 PG), 93% solids epoxy (Sterling® ER-610), and 100% solids VPI epoxy (Sterling® Y-833), and waterborne epoxy (Schenectady Isopoxy® 800). Burnout resistance and dielectric strength are compared to unexposed values for each varnish on each of the magnet wires and also to unvarnished specimens. Weight change is reported for exposed disks of the varnishes. Weight, tensile strength, elongation, and dielectric strength are compared to unexposed values for six sheet insulations (Westinghouse Nomex-Mylar-Nomex®, Westinghouse Dacron-Mylar-Dacron®, DuPont Mylar® MO, DuPont Nomex® 410, DuPont Nomex® Mica 418, and ICI Melinex® 228). Weight change is tabulated for Insulations Sales Nomex®, Mylar®, and Nomex-Mylar® spiral-wrapped sleeving insulation. Changes in weight and dielectric strength are presented for A. O. Smith Dacron-Mylar-Dacron® and Dacron-Teflon-Dacron® lead wire insulations. Weight and breaking load changes are supplied for woven glass tape (Carolina Narrow), heat shrinkable braided polyester tape (Electrolock), glass-acrylic tape (Essex Permacel P247), and polyester tie cord (Ludlow Textiles). [see RDB3857 for a summary and RDB3858 for data on exposures to the neat refrigerants]

J. E. Field (Spauschus Associates, Incorporated), **Sealed Tube Comparisons of the Compatibility of Desiccants with Refrigerants and Lubricants,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 149-158, October 1995 (10 pages with 8 figures and 4 tables, available from JMC as RDB5A55)

This paper outlines a project and presents selected data from a study of the compatibility of bead and molded-core desiccants with 13 refrigerant-lubricant combinations. The investigation used sealed-tube tests with aluminum, copper, and steel catalysts to gauge desiccant changes. The paper introduces the test materials generically and briefly outlines the methods used. A table compares the results for R-12 and R-134a, showing total acid number (TAN) as well as fluoride, chloride, and organic acid content after aging for eight desiccants. The same data are plotted. The 16 desiccants include samples from two suppliers for each of eight types, namely 3Å and 4Å molecular sieves, alumina, silica gel, and four core types. They include 10-25% molecular sieve and alumina with carbon and 15-30% molecular sieve and alumina without carbon, each with type 3Å and 4Å molecular sieves. The lubricants include a naphthenic mineral oil (MO), alkylbenzene (AB), and two classes of polyolester (POE) lubricants - pentaerythritol ester branched acid (POE-BA) and pentaerythritol ester mixed acid (POE-MA). The refrigerant lubricant combinations examined included R-11, R-12, R-22, and R-123 with MO; R-32, R-125, and R-134a with both POE-BA and POE-MA; R-124 with AB; R-143a with POE-BA; and R-152a with AB (or with POE-MA). The paper concludes that R-22 and R-32 decomposed at nearly the same levels and that the polyolester (POE) lubricant decomposed more than did the mineral oil. The paper notes that 3Å molecular sieves performed slightly better than 4Å except in the presence of R-32.

J. E. Field (Spauschus Associates, Incorporated), **Sealed Tube Comparisons of the Compatibility of Desiccants with Refrigerants and Lubricants,** report DOE/CE/23810-54, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, May 1995 (98 pages with 67 tables, available from JMC as RDB5932)

This report presents data necessary to assess the compatibility of bead and molded-core desiccants with 13 refrigerant-lubricant combinations. It is based on sealed-tube tests with aluminum, copper, and steel catalysts. The report generically identifies the test materials, outlines the preparation and analysis methods, and summarizes the desiccant specifications for as-received samples. The moisture content and contaminants of the refrigerant specimens and the moisture content, total acid number (TAN), and ion content of the lubricants are tabulated. A table for each desiccant summarizes findings before and after aging, with both 50 and 1000 ppm of added moisture. These results include liquid and desiccant colors, copper plating, solids formation, steel corrosion, crush strength, fraction of reacted refrigerant based on gas chromatography, TAN, fluoride and chloride ion content in the liquid phase and retained in the desiccant, and organic acid retained in the desiccant. Additional tables detail the crush strength results and the acid anion and gas chromatographic analyses. The 16 desiccants include samples from two suppliers for each of eight types, namely: 3Å and 4Å molecular sieves, alumina, silica gel, and four core types. They include 10-25% molecular sieve and alumina with carbon and 15-30% molecular sieve and alumina without carbon, each with type 3Å and 4Å molecular sieves. The lubricants include a naphthenic mineral oil (MO), alkylbenzene (AB), and two classes of polyolester (POE) lubricants - pentaerythritol ester branched acid (POE-BA) and pentaerythritol ester mixed acid (POE-MA). The report presents compatibility data for each of the desiccants with the following refrigerant-lubricant combinations: R-11, R-12, R-22, and R-123 with MO; R-32, R-125, and R-134a with both POE-BA and POE-MA; R-124 with AB; R-143a with POE-BA; and R-152a with AB (or with POE-MA). It also presents a number of conclusions: Addition of 1000 ppm moisture produces no significant difference. The desiccant solid phase contains most of the chloride and fluoride ions for molecular sieves, but not always with alumina and silica gel desiccants. All of the desiccants tested contained chloride, fluoride, and - for most - sulfate and other ions when received, and they do not perform as well in retaining organic anions as they do for inorganic anions. The crush strength was reduced approximately 20% after aging. None of the desiccants tested are compatible with R-32, and steel corrosion seems to be prevalent with the core-type desiccants when aged with POE lubricants. The report notes, however, that the elevated test temperatures may have induced reactions that would not occur in actual systems at lower temperatures.

G. R. Hamed, R. H. Seiple, and O. Taikum (University of Akron), **Compatibility of Refrigerants and Lubricants with Elastomers,** report DOE/CE/-23810-14, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, January 1994 (538 pages with 519 figures and 117 tables, available from JMC as RDB4501)

This report provides extensive data on the swell behavior of 95 elastomeric gasket and seal materials in 10 refrigerants and 7 lubricants. It also details tensile strength, hardness, weight, and dimensional changes for 25 selected elastomers after thermal aging in refrigerant-lubricant mixtures. The report describes the selections as well as sample verifications for the elastomers, refrigerants, and lubricant. It then discusses resistance to solvent uptake - and resultant swell -based on the degree of crosslinking, the degree of interaction with a solvent (based on the Flory-Rehner equation), the roles of cure level and filler content, and tradeoffs with hardness and brittleness. R-123 generally resulted in the greatest swelling, but EPDM/PP/TPE, butyl rubber/PP TPE, and several vendor-supplied compositions swelled little in this refrigerant. The HFCs generally gave much less swelling than the HCFCs, though the fluoroelastomers and fluorosilicones exhibit high swelling in them. Some vendor compositions are identified that resisted swelling in all refrigerants and lubricants tested. The refrigerants tested included both hydrochlorofluorocarbons (HCFCs R-22, R-123, R-124, and R-142b) and hydrofluorocarbons (HFCs R-32, R-125, R-134, R-134a, R-143a, and R-152a). The lubricants included a naphthenic mineral oil (MO, Witco Suniso® 3GS), alkylbenzene (AB, Shrieve Zerol® 150), and three polyalkylene glycols (PAGs), namely a polypropylene glycol butyl monoether (ICI Emkarox®), a polypropylene glycol diol (Dow P425), and a modified polyglycol (AlliedSignal BRL-150). Two polyolester (POE) lubricants also were included, namely a pentaerythritol ester branched acid (Henkel Emery® 2927-A) and a pentaerythritol ester mixed acid (ICI Emkarate™ RL 22H, formerly RL 244). Appendices describe the test methodology and identify the elastomer formulations. They include polyisoprene (Natsyn™ 2200), polychloroprene (Neoprene™ W), isobutyl isoprene (Polysar Butyl), bromobutyl (Polysar X2), chlorobutyl 1068, styrene butadiene rubber (SBR 1502 and Stereon 730A and 840A), nitrile (Chemigum™ N206, N300, N615B, and N917), hydrogenated nitrile (Polysar Tomac™ A3850 and A4555), fluoroelastomers (DuPont Viton® A, B, and GF), fluorinated/chlorinated rubber (KEL-F™ 3700), epichlorohydrin homopolymer (Hydrin™ H-65), epichlorohydrin copolymer (Hydrin™ C-65 and T-75), methyl vinyl silicone (SE-33™), dimethyl silicone (SE-436U™), methyl vinyl phenyl silicone (SE-565U™) silicone (SE-3808U™), fluorinated silicone (LS-63U™), EPDM/polypropylene thermoplastic elastomer (TPE, Advanced Elastomer Systems Santoprene® 201-73, 201-87, 203-40, and 203-50), nitrile/polypropylene TPE (Geolast™ 701-87, 701-80, and 701-40), copolyester TPE (Hytrel™ 4056, 5526, G6356, and 7246), polysulfide rubber (FA™ and ST™), polyurethane (Airthane™ PET-95A and PET-60D, Cyanaprene™ A-8 and D-55, Millathane™ 76 and E-34), chlorosulfonated polyethylene (Hypalon™ 20, 40, and 4085), ethylene propylene (EPM, Vistalon™ 404 and 707), ethylene acrylic (Vamac™ G and B-124MB), chlorinated polyethylenes (Dow CM0136™ and 4211P™), ethylene propylene diene (EPDM, Royalene™ 552, 525, and 359), and EPDM/butyl TPE (Trefsin™). Another appendix iden-

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tifies ten gasket materials supplied by ARTI including filled chloroprene (Precision Rubber 2167), acrylonitrile (Precision Rubber 7507), neoprene (Garlock 2930), non-asbestos (Armstrong N-8092, Specialty Paperboard NI-2085G, Victopac 69, and Klinger C-4401), nitrile-aramid (Specialty Paperboard 2099), fluorocarbon (Parker V747-75), and neoprene (Greene, Tweed and Company 956). 95 tables present data on swell after immersions of 1, 3, and 14 days, weight change after 14 days, diameter and weight after removal, and shore hardness after 1 day of drying. 18 figures for each refrigerant and lubricant illustrate diameter changes for the exposed elastomers. Oscillating disk rheometer (ODR) curves are provided for 68 curable elastomers and thermogravimetric analysis (TGA) plots for 94 elastomers. Physical property data before exposures also are given, including modulus, tensile strength elongation at break, and hardness. Infrared (IR) and gas chromatographic (GC) analyses are summarized for the refrigerants and lubricants. A set of tables then identifies the specific refrigerant-lubricant combinations tested and changes in weight, width, thickness, tensile strength, and hardness after aging; the changes in tensile strength also are plotted.

R. Hawley-Fedder, D. Goerz, C. Koester, and M. Wilson (Lawrence Livermore National Laboratory, LLNL), **Products of Motor Burnout**, report DOE/-CE/23810-74, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 30 March 1996 (50 pages with 17 figures and 5 tables, available from JMC as RDB8402; included photographs of the test apparatus are not clear)

This report identifies and quantifies the products of motor failures in hermetic and semihermetic refrigeration compressors. The decomposition products were determined by discharging electrical pulses through refrigerant-lubricant (RL) mixtures at temperatures up to 200 °C (392 °F) and pressures up to 1380 kPa (200 psia). Tests also were performed with high electrical stress (arcing) to simulate full-scale motor failures. The three tested RL combinations were R-22 with a mineral oil, R-134a with a polyolester (POE) lubricant, and R-507A also with a POE. Comparisons showed that fewer breakdown products were found with tests at high temperatures and pressures that at room test conditions, but the main products and the total amount of breakdown products were the same. The data presented show that the bench-scale electrical breakdown test does not duplicate motor failure conditions. Moreover, published information from other studies indicates that the bench test does not accurately predict the results of motor failure from alternating-current (AC) carryover. The report documents difficulties encountered in performing breakdown tests in hermetic motors, the test approaches used, and the findings of a literature search on breakdown products of refrigerants.

R. Hawley-Fedder, D. Goerz, C. Koester, and M. Wilson (Lawrence Livermore National Laboratory, LLNL), **Investigation of the Breakdown Products Produced from Electrical Discharge in Selected CFC Replacement Fluids,** *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 163-168, July 1996; republished as report DOE/-CE/23810-72C, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 1996 (10 pages with 1 figure and 3 tables, available from JMC as RDB6833)

evaluation of R-22, R-134a, and R-507A under simulated alternating current (AC), direct current (DC), and pulsed breakdown conditions; energy deposition into each fluid; major breakdown products after electrical testing under ambient and elevated pressure and temperature and after an AC carryover arc condition in hermetic motors

T. Iizuka, A. Ishiyama, H. Hata, and T. Sugano (Hitachi Limited, Japan), **Study of Technology for Refrigerant Applications 1. Materials Compatibility for HCFC-22 Alternative Refrigerants**, presented at the Fifth International Refrigeration Conference (Purdue University, West Lafayette, IN), July 1994; published as a late paper in *Proceedings of the 1996 International Refrigeration Conference at Purdue,* edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 515-520, July 1996 (6 pages with 6 figures and 5 tables, limited copies available from JMC as RDB4866)

This paper presents the findings of materials compatibility tests of R-32, R-125, and R-134a with basic fabrication materials for refrigerators, air conditioners, and other refrigeration systems. A table compares the minimum chemical bond strength, ozone depletion potential (ODP), global warming potential (GWP), and flammability of the three refrigerants and R-22, R-32/134a (30/70), and R-407C [R-32/125/134a (23/25/52)]. Based on these data, the paper notes that all hydrofluorocarbons (HFCs) are thermally more stable than R-22. A second table gives the viscosity at 40 and 100 °C (104 and 212 °F), pour point, and lower critical solution temperature (LCST) in R-32, R-125, and R-134a for eight polyolester (POE), two carbonate or polycarbonate, and one mineral oil lubricants. The POEs include trimethylolpropane (TMP), pentaerythritol, and neopentylglycol types. Their miscibilities with the cited HFCs and total acid number (TAN) values are plotted, the latter as functions of water and epoxy additive contents. Tables summarize the results of sealed-tube tests of R32, R-125, and R-134a in the presence of aluminum, copper, and iron catalysts. The paper then discusses hydrolysis of the POEs into carboxylic acid and alcohol. It also discusses prevention methods, including drying and use of epoxy-type catchers. Plots show the relative oligomer extraction and tensile strength change of polyethylene terephthalate (PET) motor insulating films. Two tables summarize tests of modified ester-imide, polyamide imide, double coated magnet wires and of six molecular sieve desiccants (UOP 4A-NRG, XH-5, XH-6, XH-7, XH-9, and XH-10C). The paper concludes that TMP ester with epoxy-type acid catcher offers good miscibility with HFCs and improved hydrolytic stability. Further, motor materials for insulating film and magnet wires for R-22 can be used in HFC systems without modification. Developmental molecular sieve XH-10C is the indicated as the best choice at low temperatures with R-32, and drop-in tests with the cited materials yielded satisfactory results.

A. Ishiyama, T. Iizuka, K. Kawashima, K. Sekigami, H. Hata, and T. Sugano (Hitachi Limited, Japan), **Study of Technology for Refrigerant Applications 2. Lubrication of Rotary Compressors in HFC-Based Alternatives**, unpublished paper presented at the Fifth International Refrigeration Conference (Purdue University, West Lafayette, IN), July 1994 (6 pages with 6 figures and 5 tables, limited copies available from JMC as RDB4867)

S. A. Kujak and T. D. Waite (The Trane Company), **Compatibility of Motor Materials with Polyolester Lubricants: Effect of Moisture and Weak Acids**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 425-429, July 1994 (5 pages with 6 tables, RDB-4857)

compares results for R-134a with polyolester lubricant to results for R-22 with mineral oil

M. S. Sefton, S. V. Mortlock, M. A. Harding (ICI Films) S. Corr, and G. Tompsett (ICI Chemicals and Polymers, Limited, UK), **Polyester Insulation Materials, HFC Refrigerants, and Ester Lubricants**, *Proceedings: Electrical Electronics Insulation Conference and Electrical Manufacturing and Coil Winding Conference (EEIC/ICWA),* Rosemont, IL, 505-506, October 1993 (2 pages with 2 figures and 1 table, RDB3A23)

This paper presents compatibility tests of polyethylene terephthalate (PET) insulating materials with R-32, R-125, and R-134a with mixed-acid, polyolester (POE) lubricants (ICI Emkarate™ RL 22H and 32S). Comparative data also are presented for R-12 and R-22 with mineral oils (MO, Shell Clavus 32 and Witco Suniso® 3GS). The tests examined both standard and low oligomer PET films (ICI Melinex® 226 and 228, respectively), used as insulation materials in motors for hermetic compressors. The paper outlines autoclave tests at 140 °C (284 °F) for 14 and 28 days at autogenous pressures (approximately 4 MPa, 600 psig) followed by tensile testing and oligomer extraction analysis. The results indicate that the R-134a/POE mixture is considerably more aggressive in terms of oligomer extraction than R-12/MO or R-22/MO mixtures. However, low oligomer PET films show similar behavior for the same refrigerant/lubricant systems. Two figures compare oligomer extraction for standard and low oligomer films in R-12/MO, R-22/MO, R-32/POE, R-125/POE, and R-134a/-POE. A table summarizes changes in tensile strength and extension to break for the two PET types for R-32, R-125, and R-134a with POEs.

J. S. Thrasher, R. Timkovich, H. P. S. Kumar, and S. L. Hathcock (University of Alabama), **Moisture Solubility in Refrigerant 123 and Refrigerant 134a,** *Transactions* (Winter Meeting, New Orleans, LA, January 1994), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 100(1), 1994 (rdb4A32)

R-123, R-134a

S. G. Sundaresan (Copeland Corporation), **Characterization of Solid Contaminants in Air-Conditioning Systems and their Effect on Compressor Reliability**, *Proceedings of the 1984 International Compressor Engineering Conference at Purdue* (11-13 July 1984), Purdue University, West Lafayette, IN, 408-417, July 1984 (10 pages with 9 figures and 3 tables, RDB8614)

describes the devices and techniques to trap solid contaminants in operating systems; summarizes a laboratory evaluation to characterize the weight, size distribution, and elemental analysis of solid residue particles; comments on current protection methods and their use to achieve system cleanliness; outlines contaminant effects on clogging, stiction, wear, and chemical breakdown; identifies a combination of contaminants found in refrigerants and lubricants from field samples, including iron oxide, dust, stainless steel, copper oxide, aluminum alloy, copper chloride, brass, polytetrafluoroethylene (PTFE, DuPont Teflon®), formulated as a standard test, to enable durability testing

S. G. Sundaresan (Copeland Corporation), **Characterization of the CFC Issues Relating to the Air-Conditioning and Refrigeration Industry, Part 2: Standards for Acceptable Levels of Contami-**

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nants in Refrigerants, *International Journal of Refrigeration* (IJR), 11:213-216, 1988; republished in *Status of CFCs - Refrigeration Systems and Refrigerant Properties* (proceedings of the meetings of IIR Commissions B1, B2, E1, and E2, Purdue University, West Lafayette, IN), International Institute of Refrigeration, Paris, France, July 1988 (4 pages with 1 table, RDB8615)

describes the background, current practices, objectives, and results of an Air-Conditioning and Refrigeration Institute (ARI) committee convened to develop voluntary standards for the cleanliness and purity of refrigerants (later ARI Standard 700); describes the effects of moisture, mineral and organic acids, oils, high boiling point residues, air carbon dioxide, other noncondensible gases, solids, and other refrigerants; considers abrasive, conductive, spatial, corrosive, pressure, stability, freezing, safety, performance, and durability effects in an attempt to determine maximum allowable contaminant levels,

Develop Corrosion Data with Metals of Construction and New Refrigerant/Lubricants at Various Moisture and Organic Acid Levels, research project 887-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, September 1995 - October 1996, extended to 1998 (ASH0887)

This research project will determine the corrosion rates for selected metals in the presence of low molecular weight, organic acids. These acids result from hydrolysis of polyolester lubricants and subsequent reactions. The study also will quantify the concentrations of reacting acids and reaction products as functions of exposure times. The contractor for the project is Spauschus Associates, Incorporated, led by J. E. Field; it is sponsored by Technical Committee 3.2, *Refrigerant System Chemistry.*

Handbook for Rubber Materials in Automotive Air Conditioning Applications, *Rubber Handbook,* Santech Industries, Incorporated, Fort Worth, TX, November 1993 (24 pages with 11 figures and 11 tables, available from JMC as RDB4139)

This bulletin presents the uses of and considerations for rubber in mobile air-conditioning (MAC) applications, noting that all applications are static. It illustrates the sealing mechanisms of o-rings and outlines the temperatures encountered - as high as 149 °C (300 °F) - in representative systems. It then identifies R-12 and R-134a as the refrigerants used by original equipment manufacturers, but notes that R-22 or other refrigerants are used in some truck and trailers systems. It suggests three refrigerant-lubricant combinations as the most common, namely R-12 with mineral oil (MO), R-134a with polyalkylene glycol (PAG), and for retrofit of existing systems R-134a with polyolester (POE). The remainder of the brochure discusses compatibility for them with three rubber materials that account for almost all rubber used in automotive applications: nitrile butadiene rubber (NBR, nitrile or Buna-N), hydrogenated nitrile butadiene rubber (HNBR also including highly saturated nitrile, HSN), and chloroprene rubber (CR including neoprene, neoprene W, and polychloroprene). The bulletin lists the ingredients of a simple NBR, but points out that there are thousands of compounds tailored for different applications. After discussing seal force, the bulletin compares the three rubbers after aging at 100 and 148 °C (212 and 300 °F) for 70 hours. The bulletin describes ASTM D395 compression set (heat aging), ASTM D471 fluid immersion, and Santech internal QP409 refrigerant-lubricant immersion test methods. It then presents test results for sample o-rings made of HNBR (Santech ST7470), HNBR (Santech ST4470), and CR (an unidentified neoprene compound). The bulletin also discusses comparative costs of the three elastomers and outlines rubber uses by major automobile and MAC compressor manufacturers. The bulletin concludes with recommendations for rubber material selections.

R-123

R. G. Doerr (The Trane Company), **Absorption of HCFC-123 and CFC-11 by Epoxy Motor Varnish,** paper 3621, *Transactions* (Annual Meeting, Baltimore, MD, June 1992; previously presented at Annual Meeting, Indianapolis, IN, June 1991), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 98(2):227-234, 1992 (8 pages with 9 figures, RDB-2606)

This paper summarizes a study to determine the parameters that influence absorption of R-11 and R-123 by varnishes and the effect of the absorbed refrigerants on chemical and physical properties. These varnishes hold motor windings together and act as secondary electrical insulation, filling in voids created during the winding process. Interest in the subject stems from observations that motor varnishes can absorb considerable amounts of R-123 with varying effects. The effects of cyclic and continuous exposures at high temperature and pressure, relative rates of absorption and desorption, existence of an equilibrium absorption value, and effects of temperature on the rate of absorption and the equilibrium are discussed. The experimental procedure, based on weight gain during thermal aging followed by drying, is outlined. Four varnishes were tested; they are identified as a recently introduced solventless type, a common solvent-based type, a 100% solids type, and a water-borne epoxy. The paper concludes that absorption is the same for cyclic and continuous exposures, that desorption is extremely slow to nonexistent at 21 °C (70 °F), and that full desorption would require in excess of 1000 hours at 121 °C (250 °F). It also notes that absorption increases until an equilibrium is established; while the rate differs widely for different varnishes, the rate is more rapid at higher temperatures. The equilibrium value is linearly dependent on temperature, with greater absorption at lower temperatures, for R-123, but relatively independent of temperature for R-11. The paper outlines two key implications for compatibility testing: 1) low temperature and pressure may be a more severe environment for materials than high temperature and pressure, and 2) tests must be continued long enough to be certain that equilibrium is reached at lower temperatures.

H. B. Ginder, **Compatibility Test - 15# Carbon Bursting Disk (2.5")**, York International Corporation, York, PA, July 1989 (1 page, available from JMC as RDB0011)

A 64 mm (2½") carbon bursting disk was immersed in R-123 at room temperature for 16 days. Subsequent testing for leaks and porosity, using R-22, indicated that the disk did not develop leaks.

H. B. Ginder, **Compatibility Test - O-Rings, Gasket, Oil Filter, Etc.,** York International Corporation, York, PA, July 1989 (1 page with 1 table, available from JMC as RDB0009)

A table summarizes the swelling of various materials immersed in R-123 and R-11. The materials include elastomeric (DuPont Viton®, Buna™ N, and neoprene) o-rings, a Buna™ N bushing, and components of a Kaydon oil-line filter (cork and Buna™ N gaskets, pleated paper, and adhesive). Quantitative results are presented after a two week exposure at room temperature in a mixture of 90% refrigerant and 10% naphthenic oil. The R-123 test samples swelled considerably more than the R-11 samples. The Buna N bushing swelled 79% in R-123, as compared to 7.1% in R-11. The document concludes that Buna N formulations are not too compatible with R-123, but that Viton and neoprene appear to be acceptable. Compatibility concerns also are cited for the gaskets and adhesive in the oil filter.

T. P. Gross, **Compatibility Test - Green-Colored Viton O-Ring,** York International Corporation, York, PA, July 1989 (1 page, available from JMC as RDB-0012)

Swell data are presented for green-colored fluoroelastomeric (DuPont Viton® o-rings) immersed in R-123 and R-11 for three weeks at room temperature. The o-rings showed initial linear swell of 19.8% in R-123, which changed to 4.4% after drying overnight. Samples exposed to R-11 showed initial linear swell of 3.0%. The elastomers exhibited no significant loss in physical properties in either fluid.

T. P. Gross, **Compatibility Test - Loctite Sealants (Pipe Sealant with Teflon, Grade AV),** York International Corporation, York, PA, July 1989 (1 page, available from JMC as RDB0010)

Two Loctite® compounds (pipe sealant with DuPont Teflon® and Grade AV) were applied to threaded fittings and tested with liquid R-123. The report indicates that they appear to be compatible with R-123, based on a seven-day period of exposure and curing. The test procedure and curing considerations for sealants are discussed.

Decomposition Rates of R-11 and R-123, Carrier Corporation, Syracuse, NY, September 1989 (3 pages with 3 figures, available from JMC as RDB-0019)

The fraction of R-123 that decomposes in solution with alkylbenzene lubricant after 14 days is plotted as a function of temperature. Less than 1% decomposition was measured at 82 and 121 °C (180 and 250 °F), but this increased to 6.2% at 177 °C (350 °F). Decomposition of R-11 and R-123 after 4 and 14 days, respectively, at 121 °C (250 °F) is compared for mixtures of 5% lubricant by weight. One alkylbenzene (Zerol® 300) and four mineral oils (Mobil DTE Heavy Medium, Mobil DTE 26, Rando HD-68, and Witco Suniso® 4GS) were tested.

Elastomer Immersion Tests for Fluorocarbon-123, technical report NIST-8, Freon® Products Laboratory, E. I. duPont de Nemours and Company, Incorporated, Wilmington, DE, undated circa 1988 (5 pages with 2 tables, available from JMC as RDB0304)

Results are summarized for immersion tests of 13 elastomers in R-123 for up to seven days at 75 and 130 °F (24 and 54 °C). Quantitative results of the linear-swell tests are provided, including intermediate and final changes in length and weight as well as the fraction of extractables. Qualitative changes in appearance and physical properties of the elastomers and in the appearance of the liquid are tabulated. The tested elastomers were two urethane rubbers

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(Uniroyal Adiprene® C and Adiprene® L), a hydrocarbon rubber (DuPont Nordel®), a fluoroelastomer (DuPont Viton® A), a silicone rubber (General Electric SE-361), a nitrile silicone rubber (NSR-X5602), a synthetic rubber (DuPont Hypalon® 40), natural rubber, polysulfide rubber (Thiokol® FA), Buna™ N, Buna™ S, chloroprene (neoprene W), and Butyl™. Of those tested, only Thiokol FA appears suitable for use and prolonged contact with R-123.

Evaluation of Epoxy Varnish Materials for Alternative Refrigerant HCFC-123, report NIST-13, Chemistry Laboratory, The Trane Company, La Crosse, WI, 25 August 1989 (9 pages with 8 tables, available from JMC as RDB0034)

This report presents measured and observed findings for sealed-tube tests varnishes used as insulation for motors in hermetic compressors. Results are tabulated before and after thermal aging in air, R-11, and R-123 for P. D. George Sterling® 364, water-borne epoxy (Schenectady Isopoxy® 800), Schenectady 8620, Epoxylite 477, and solvent epoxy (Sterling® 923) varnishes. The exposures were made at 121 °C (250 °F) for 168 hours (1 week). Changes to the pre-exposure conditions are reported immediately after exposures and after drying for different periods, depending on the material. A final table summarizes extraction measurements on the varnishes after exposures. The preparatory curing conditions for the samples also are documented.

HCFC-123 Compatibility with Teflex NPG V-214 O-Rings Covered with High Density Teflon, report NIST-11, Chemistry Laboratory, The Trane Company, La Crosse, WI, 16 March 1989 (1 page, available from JMC as RDB0032)

Results of swell testing tetrafluoroethylene (TFE, DuPont Teflon®) coated DuPont Viton® o-rings in R-123 at 100 °C (212 °F) are reported. The Teflon® coating was permeated, causing the Viton core to swell. Testing stopped after 72 hours due to o-ring failure.

Material Compatibility of Alternative Refrigerants: Usability/Compatibility of R-123 Received from Refrigerant Suppliers, report NIST-2, Chemistry Laboratory, The Trane Company, La Crosse, WI, 15 April 1988 (2 pages with 1 table, available from JMC as RDB0023)

This report of chemical analyses addresses the compatibility of R-123 samples from AlliedSignal and DuPont Chemicals with red neoprene 2337 elastomer material. Test rings were exposed to R-123 in both vapor and liquid phases for 168 hours at 77 °C (170 °F) using Trane Standard Test Method 3.7-04. Control samples were similariy exposed to R-11. Cross-sectional diameter, volume swell, and durometer hardness are tabulated before and after exposures. Some extraction of processing and/or base oils was observed with all three refrigerant samples. No precipitation of waxlike materials, cracks, or blisters were evident in any of the refrigerants. The increases in diameter and volume and decreases in durometer hardness were lower in R-123 than in R-11. The differences between results from the two R-123 samples were minor.

Material Compatibility of Alternative Refrigerants: Usability/Compatibility of R-123 Received from Refrigerant Suppliers, report NIST-3, Chemistry Laboratory, The Trane Company, La Crosse, WI, 15 April 1988 (4 pages with 2 tables, available from JMC as RDB0024)

Swell tests of elastomeric compounds in R-11 and R-123 at 77 °C (170 °F) for 72 hours are reported. The elastomers included yellow nitrile 7507, red neoprene 2337, and green neoprene 2167. Quantitative data are presented for volume swell, cross-sectional diameter, and durometer hardness. Nitrile swelled 400-600% more in R-123 than in R-11. The neoprene samples exposed to R-123 exhibited less or comparable swelling to those exposed to R-11.

Material Compatibility of Alternative Refrigerants: Usability/Compatibility of R-123 Received from Refrigerant Suppliers with Elastomer Materials, report NIST-4, Chemistry Laboratory, The Trane Company, La Crosse, WI, 10 May 1988 (3 pages with 2 tables, available from JMC as RDB0025)

Swell and durometer test data are tabulated for yellow nitrile 7507, red neoprene 2337, and green neoprene 2167 test rings exposed to 50/50 mixtures of R-11 and R-123 with 250 SUS white oil. The tests were repeated for separate samples of R-123 from AlliedSignal and DuPont Chemicals. Samples were aged in stainless steel test vessels for 3 days (72 hours) at 77 °C (170 °F). Cross-sectional diameter, volume swell, and durometer hardness were measured both before and after exposures, for both the vapor and liquid phases of the refrigerants, and compared. The hardness measurements were repeated after 2-3 days of drying to allow off-gasing.

Material Compatibility of Alternative Refrigerants: Compatibility of R-123 Received from Refrigerant Suppliers with Proposed Elastomer Materials, report NIST-5, Chemistry Laboratory, The Trane Company, La Crosse, WI, 6 June 1988 (2 pages with 1 table, available from JMC as RDB0026)

Measurements of weight, volume, density, dimensions, and durometer hardness are reported for polysulfide rubber (Morton Thiokol® ST). Data are compared before and after exposures to both the vapor and liquid phases of R-123. Aging was performed in stainless steel test vessels for 3 days (72 hours) at 77 °C (170 °F). The tabulated data summarize measurements for tests in the refrigerant alone and in a 50/50 mixture with 250 SUS white oil. The tests were repeated for separate samples of R-123 from AlliedSignal and DuPont Chemicals. Data for exposures to the AlliedSignal R-123 refrigerant without lubricant were lost, due to an experimental problem, and were not remeasured. The document concludes that this rubber formulation would not be acceptable as an elastomer for use in a R-123 environment, but it does not rule out use of other polysulfide rubbers. The test data suggest that this rubber compound is affected more severely by 100% R-123 than by the mixture of R-123 and lubricant.

Material Compatibility of Alternative Refrigerant 123: Elastomer Chemistry of and Specifications for Chloroprene, report NIST-8, Chemistry Laboratory, The Trane Company, La Crosse, WI, 10 November 1988 (2 pages with 1 table, available from JMC as RDB0029)

This document compares the elastomer chemistry of chloroprene rubber for use in R-123. The formulations tested included 2337 (red dot), 2167 (green dot), and 2347 (new compound) o-rings as well as 2167 (green dot) cord ring. Chemical properties obtained from infrared spectra, volumetric swell, and durometer hardness were compared as received, after heat aging in air for 168 hr at 100 °C (212 °F), and after thermal aging at the same conditions in ASTM #3 oil, 250 SUS white oil, and R-123 vapor. Tests also were performed after immersion in R-11 liquid, R-11 vapor, and R-123 liquid for neoprene 2347. The resulting data are tabulated.

Material Compatibility of Alternative Refrigerant 123: Physical Properties of O-Rings for Applicability in Alternative Refrigerant 123 and Refrigerant 11, report NIST-7, Chemistry Laboratory, The Trane Company, La Crosse, WI, 27 October 1988 (2 pages with 2 tables, available from JMC as RDB-0028)

The tensile strength, elongation, and fluid resistance of neoprene 2347 (size 222) o-rings were tested. Measured values were compared for materials as received, after heat aging in air for 168 hr at 100 °C (212 °F), and after thermal aging at the same conditions in ASTM #3 oil, 250 SUS white oil, R-11, and R-123. Heat aging was performed and fluid resistance was measured in accordance with ASTM D573 and D471, respectively. The tabulated data indicate less change for R-123 than for R-11, and that the decrease in tensile strength and elongation for R-123 is similar to that after immersion in ASTM #3 oil.

Material Compatibility of Alternative Refrigerant 123: Short Term Suitability of Chloroprene Sheet Gasket Material, report NIST-6, Chemistry Laboratory, The Trane Company, La Crosse, WI, 7 October 1988 (1 page, available from JMC as RDB-0027)

Results are qualitatively summarized for compression and flexibility tests of Reinz chloroprene sheet gasket material exposed to R-123. The exposures were for 24 hour at 25 °C (77 °F) and at 100 °C (212 °F). All samples (hot and cold) failed when folded before reaching a 180° angle.

Metal Corrosion Tests with [HC]**FC-123 and Distilled Water**, report NIST-10, E. I. duPont de Nemours and Company, Incorporated, Wilmington, DE, undated (5 pages with 2 tables, available from JMC as RDB0306)

Compatibility results of R-123 and distilled water with cold-rolled steel 1020, stainless steel 304, nickel, monel, copper, aluminum 2S, zinc, and magnesium alloy FS-1 are reported for dry and wet conditions. Results are tabulated at the liquid boiling point after exposure for 100 hours and after 100 days at 55 °C (130 °F). Decomposition of the R-123, metal corrosion rates, and the appearances of the liquid and metal are presented. R-123 was judged suitable with all of the metals under dry-test conditions, but suitable only with the stainless steel after 100-day wet exposure. Additionally, only the stainless steel, nickel, and monel showed no corrosion after the 100-day wet-exposure test.

Motor Insulations in R-123 and R-134a, Carrier Corporation, Syracuse, NY, September 1989 (2 pages with 2 figures, available from JMC as RDB-0015)

Two charts show the effects of R-123 and R-134a on cured motor insulations. XV-572, XV-587, water-borne epoxy (Schenectady Isopoxy® 800), solvent epoxy (P. D. George Sterling® U-475), and polyester (Dolphon) varnishes were tested for weight change, percent extractables, and Shore D hardness loss. Quantitative data, after aging for ten days at 93 °C (200 °F) for R-123 and at 38 °C (100 °F) for R-134a, are given.

Mutual Solubilities of Water with Fluorocarbons and Fluorocarbon-Hydrate Formation, report NIST-12, E. I. duPont de Nemours and Company,

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Incorporated, Wilmington, DE, undated (16 pages with 4 figures and 7 tables, available from JMC as RDB0308)

Test procedures and results are described for an investigation of the mutual solubility of water and of solid hydrate formation with R-123, R-124, and R-125. Measured and calculated solubility data are tabulated in the temperature range of 77-167 °C (171-333 °F) for R-123 and R-124 and 77-138 °C (171-280 °F) for R-125. Regression equations and plots of the data are provided to compare the data to prior measurements for R-22, R-113, and an unidentified fluid. Solubility coefficients are plotted for these fluorocarbons in water for 0-120 °C (30-250 °F) at saturated vapor pressure conditions. The fraction of fluorocarbon by weight in water are similarly presented and plotted at saturated vapor and atmospheric pressures. The results coupled with those of earlier work indicate that R-125, R-134a, R-142b, and R-152a form solid water hydrates, but that R-123 and R-124 do not. The document discusses implications of the findings on specifications for water content in the refrigerants examined.

Plastic Immersion Tests in Fluorocarbon-123, report NIST-7, E. I. duPont de Nemours and Company, Incorporated, Wilmington, DE, undated (5 pages with 2 tables, available from JMC as RDB-0303)

Results of compatibility tests are presented for 13 plastics, after immersion for four hours at 24 °C (75 °F) and after thermal-aging for 100 hours at 54 °C (130 °F) in R-123. The plastics included linear polyethylene (Alathon® 7050), polypropylene (Alathon® 9140), cast methylmethacrylate resin (Lucite®), nylon (DuPont Zytel® 101), tetrafluoroethylene (TFE, DuPont Teflon® type 1), polycarbonate resin (GE Lexan®), ABS polymer (Kralastic®), polystyrene (Styron™ 475), epoxy (G-10-3675), ethyl cellulose, acetal resin (DuPont Delrin® 500X), polyvinyl alcohol, and unplasticized polyvinyl chloride. Quantitative data are presented for length change, weight change, and for percent extractables. The appearances of the plastic and liquid R-123 are described. The linear polyethylene, nylon, epoxy, acetal, and polyvinyl chloride plastics tested were judged to be compatible with R-123.

Polymer/Elastomer Performance in R-123 and R-134a, Carrier Corporation, Syracuse, NY, September 1989 (4 pages with 3 figures, available from JMC as RDB0018)

Two graphs compare swell for polymers and elastomers in R-11 and R-123 at room temperature and at 93 °C (200 °F). The materials include a nitrile copolymer, fluoroelastomer (DuPont Viton® A), isoprene (neoprene), nylon, phosphazene (Eypel-F), polytetrafluoroethylene (PTFE, Gylon), polyolefin (Alcryn), polypropylene, olefinic thermoplastic (Geolast®), and polyester thermoplastic (DuPont Hytrel®). R-123 produced much greater swelling than did R-11. Quantitative values are given for swell and extractables of elastomeric materials in R-134a at 93 °C (200 °F) for ten days. These materials include Gylon, neoprene, nitrile, nylon 6/6, polypropylene, and Viton A.

Refrigerant Breakdown Voltage, AlliedSignal Incorporated, Buffalo, NY, 1 May 1990 (1 page with 1 table, available from JMC as RDB0512)

Refrigerant breakdown voltages, as determined by ASTM D-2477-84, are tabulated for R-11, R-12, R-22, R-123, and R-134a at 21 °C (70 °F) and 93 °C (200 °F).

Sealed-Tube Stability Test Results: Alternative Refrigerants, Carrier Corporation, Syracuse, NY, September 1989 (1 page with 1 table, available from JMC as RDB0020)

A table summarizes the decomposition fraction of R-11, R-12, R-123, and R-134a with Witco Suniso® 3GS and Mobil DTE 26 mineral oils and with Zerol® 150 and Zerol 300 alkylbenzene lubricants. No decomposition was detected for R-134a; some R-12 decomposed into R-22. R-123 decomposed less than R-11 for all four lubricants.

Stability of CFC-11 and HCFC-123, report NIST-12, Chemistry Laboratory, The Trane Company, La Crosse, WI, 17 April 1989 (3 pages with 1 table, available from JMC as RDB0033)

Sealed-tube test results are compared for R-11 and R-123 after exposure to 250 SUS white mineral oil and metallic catalysts (aluminum, copper, and steel). Qualitative and quantitative decomposition effects are presented after 168 hours at 100 °C (212 °F), 121 °C (250 °F), and 150 °C (302 °F). The thermal stability of R-123 and oil was judged to be greater than the thermal stability of R-11 and oil.

Teflex O-Rings, Size 214, Sealmore Industries, report NIST-10, Chemistry Laboratory, The Trane Company, La Crosse, WI, 27 January 1989 (1 page with 1 table, available from JMC as RDB0031)

A table compares the swell properties of Teflex o-rings in R-11, R-123, and in 250 SUS white oil with each refrigerant in a 50% refrigerant mixture. Quantitative results are presented after a 70-hour exposure at 77 °C (170 °F). The R-123 samples exhibited a volume change three-times higher than those of the R-11 samples. However, the o-ring density changes were comparable for the R-11 and R-123 refrigerant-lubricant mixtures.

Viton O-Ring and Cord Ring Swell Data in Both R-11 and HCFC-123, report NIST-14, Chemistry Laboratory, The Trane Company, La Crosse, WI, 13 September 1989 (1 page with 1 table, available from JMC as RDB0035)

Comparisons are presented for immersion of fluoroelastomer (DuPont Viton® o-rings and cord rings in R-11 and R-123. Data are tabulated for 70-hour exposures at 77 °C (170 °F). The volume change of the Viton materials in R-123 was found to be approximately three times that for R-11.

UL 984 Tests with R-123 and Oils, Carrier Corporation, Syracuse, NY, undated circa September 1989 (1 page with 1 table, available from JMC as RDB0016)

A table summarizes modified UL 984 tests of motor materials aged at 82 °C (180 °F) for 60 days. Control results are compared to those after separate exposures to R-11 and R-123 mixed with 5% Mobil DTE 26 mineral oil, Zerol® 150 alkylbenzene oil, and Rando HD-68. Insulation failures (1 ma current leakage to ground after 1 minute at 1.5 kV) and breakdown voltages are reported. Results are summarized for polyester-imide magnet wire, Dacron-Valox® lead wire, DuPont Teflon® wire sleeving, DuPont Mylar® end cap, Mylar-Dacron® thermosleeve, Mylar® and Melinex® slot liners, and Mylar and Melinex phase separators. Breakdown voltages of 2.7-17.0 kV, but no current leakage failures, are indicated.

R-124

P. R. Reed (DuPont Chemicals) and H. O. Spauschus (Spauschus Associates, Incorporated), **HCFC-124: Applications, Properties, and Comparisons with CFC-114,** *ASHRAE Journal*, 33(2):-40-41, February 1991 (2 pages, rdb4931)

recommends use of alkylbenzene (AB) lubricants for R-124, since petroleum-based refrigeration oils have limited miscibility with this refrigerant; chemical stability of R-124 with AB is significantly better than that of R-114 with mineral oil (MO) and the tendency for copper plating is greatly reduced; stability of R-124/AB mixtures is excellent even in the presence of high (1,000 ppm) moisture levels; while the failure load for R-124/AB lubricity is lower than that of R-114/MO, additives based on butylated triphenyl phosphate (BTP) raise the failure load above that for R-114/MO without significant degradation of stability

P. R. Reed (DuPont Chemicals) and H. O. Spauschus (Spauschus Associates, Incorporated), **HCFC-124 Applications and Properties: Comparisons with CFC-114,** presentation charts prepared by Spauschus Associates, Incorporated, for E. I. duPont de Nemours and Company, Incorporated, Wilmington, DE, undated (22 pages with 9 figures and 1 table, available from JMC as RDB1206)

The stability, miscibility, and lubricity of R-124 are compared to those of R-114. Qualitative data are presented for sealed-tube tests with metals (copper and steel) and unspecified 300 SUS mineral oils (paraffinic and naphthenic) and with an alkylbenzene lubricant after 14 days at 175 °C (350 °F). The effects of high moisture content and of lubricant additives on refrigerant stability also are discussed. Alkylbenzene lubricants were judged to be the most suitable for use with R-124.

R-134a

S. Corr, P. D. Guy, R. D. Gregson, N. M. Sammes, G. Tompsett (ICI Chemicals and Polymers, Limited, UK), and T. W. Dekleva (ICI Americas, Incorporated), **Materials Compatibility and System Stability Studies with R-134a and Alternative Lubricants,** seminar presentation at the ASHRAE Annual Meeting (St. Louis, MO), ICI Americas Incorporated, New Castle, DE, 12 June 1990 (30 pages with 23 charts, RDB2523)

P. D. Guy, G. Tompsett (ICI Chemicals and Polymers, Limited, UK), and T. W. Dekleva (ICI Americas, Incorporated), **Compatibilities of Nonmetallic Materials with R-134a and Alternative Lubricants in Refrigeration Systems,** paper AN-92-5-4, *Transactions* (Winter Meeting, Anaheim, CA, January 1992), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 98(1):804-816, 1992 (13 pages with 17 tables, RDB2104)

This paper reviews the compatibility of nonmetallic materials with R-134a and associated lubricants, based on sealed-tube tests as well as analytical investigations of compressor life tests and field evaluations. The test and analytical methods used also are reviewed. The materials addressed include ethylene propylene dimer monomer (EPDM) rubber, fluorinated polymer, natural rubber, nitrile rubber, nylon, and polyethylene terephthalate (PET). Data on weight, volume, tensile-strength, and elongation change

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as well as on hardness are compared to those for R-12 with naphthenic mineral oil. The paper notes that while an enormous amount of information has been developed by industry for compatibility of alternative refrigerants with associated lubricants and materials, most of it has not been published.

J. G. Johnson and T. E. Watson (McQuay International, then SnyderGeneral Corporation), **Refrigerant 134a Compatibility with Centrifugal Chillers**, paper 5.1, *Proceedings of the International Seminar on New Technology of Alternative Refrigerants - Lubricants and Materials Compatibility* (Tokyo, February 1993), Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 83-88, February 1993 (6 pages with 4 figures and 6 tables, preprint available from JMC as RDB3117)

This paper reviews requirements for use of R-134a in chillers with centrifugal compressors. The paper compares the thermodynamic properties of R-134a to those of R-12 and R-500. Data are tabulated to substantiate 4% lower mass flow, but higher isentropic lift requirements. Heat transfer characteristics also are compared, noting an overall improvement of 12% in condensers for R-134a over R-12 and 2-10% in evaporators. A plot compares the film coefficients for pool boiling for a range of typical heat fluxes. Scaling opportunities through dimensional analysis, to attain a range of capacities and accommodate different refrigerants, are illustrated. Tabular data compare efficiency with R-134a or R-500 to that with R-12. The paper then reviews materials compatibility issues, with attention to elastomers, plastics, metals, and motor materials. A plot compares swell for three nitriles with R-134a, polyolester mixed acid, polyolester branched acid, and naphthenic mineral oils. Stability data based on sealed-tube tests, are compared for R-12, R-22, R-123, R-134a, and R-500 with associated lubricants. The paper addresses lubricant solubility, miscibility, and lubricity. A plot shows oil return with R-12 and R-134a, with mineral oil and pentaerythritol ester respectively, for a flooded evaporator. Test results are tabulated for a retrofit from R-500 to R-134a, showing a 10% loss in capacity and 2% increase in efficiency. Conversion requirements are outlined from R-12 to R-134a. A final table compares pool boiling for R-12 with mineral oil, R-134a with ester, and the latter pair with 5% residual mineral oil. The paper concludes that R-134a with ester lubricants offers similar or improved compatibility and better oil return and heat transfer. The efficiency is nearly the same for R-12, R-134a, and R-500. Conversions of R-500 machines can achieve 90% of original capacity without hardware changes. Retrofit of R-12 chillers requires changing the gear set and impeller, but results in comparable efficiency.

J. G. Johnson, **R-134a, R-123, and Mineral Oil Compatibility with Steel, Aluminum, and Copper,** McQuay International (then SnyderGeneral Corporation), Staunton, VA, 4 September 1990 (4 pages with 1 figure and 1 table, available from JMC as RDB0902)

The chemical and thermal stability of R-123 and R-134a with Witco Suniso® 4GS mineral oil in the presence of ferrous and nonferrous metals were compared to that of R-12 and R-500 under the same conditions. Stability was gauged using sealed-tube tests for 14 days at 175 °C (350 °F); test results are compared by gas chromatography, to identify decomposition products, and by visual analysis. The metals used for the tests were Sandvik valve steel, OFHC copper wire, and aluminum 85 bearing material. R-134a was found to be superior to R-12 and R-500 in stability and reactivity, but immediate decomposition was evident for R-123.

E. D. Lawler, **HFC-134a and Mineral Oil Materials Compatibility with Hermetic Motor Insulation System for McQuay PEH048/050 Centrifugal Water Chillers**, McQuay International (then SnyderGeneral Corporation), Staunton, VA, 29 August 1990 (2 pages with 4 tables, available from JMC as RDB0901)

The compatibility of R-134a and mineral oils (both naphthenic and paraffinic) with the hermetic motor insulation materials used in centrifugal water chillers are examined. Baseline tests were run with R-12 and naphthenic oil for comparison purposes. Results are presented for varnish bonding for amide-imide-polyester film and dielectric retention of copper magnet wire with and without varnish treatment. Results also are summarized for retention of flexibility for DuPont Mylar®, DuPont Nomex®, and Dacron®-Mylar®-Dacron® sheet insulation, as well as for dielectric retention of flexible hermetic lead wire. The materials were generally unaffected. One exception was a weakening of epoxy varnish in the presence of R-134a and naphthenic oil (reduced 13.5% compared to the mixture of R-12 and naphthenic oil). Flexibility of film insulation was adequately maintained and retained dielectric was acceptable.

E. D. Lawler, **Compatibility of Various Elastomers in Refrigerant HFC-134a with Several Lubricants**, McQuay International (then SnyderGeneral Corporation), Staunton, VA, 5 September 1990 (3 pages with 3 tables, available from JMC as RDB0903)

Results of materials compatibility testing of o-rings with R-134a and naphthenic mineral oil, alkylbenzene, and polyalkylene glycol (PAG) lubricants are presented. The elastomers evaluated were nitrile HSN, nitrite ASM 3215, and neoprene ASM 3209. Thermal aging tests were conducted separately for the refrigerant and lubricants and for refrigerant-lubricant mixtures. Changes are noted for hardness, tensile strength, elongation, and volume. The property changes experienced by the elastomers were no greater than, and generally less than, those experienced when aged in the presence of either R-12 or R-22. Nitrile, however, appears to shrink slightly when soaked in alkylbenzene. The neoprene swelled slightly when subjected individually to either R-134a or the PAG, and there was an unacceptable amount of shrinkage when aged in a mixture of R-134a and 5% PAG.

A. Riemer and P. E. Hansen (Danfoss-Flensburg GmbH, Germany), **Analysis of R134a Cabinets from the First Series Production in 1990**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 501-505, July 1996 (5 pages with 3 figures and 4 tables, RDB6C31)

investigation of 20 refrigeration systems from 7 R-134a and 3 R-12 dual-circuit refrigerator/freezers after 5 years of field use; comparisons of water uptake for the XH7, molecular sieve (probably UOP XH-7 desiccants) driers used found no difference in water absorption capacity or deterioration; analysis of refrigerant samples by gas chromatography found no deterioration; examination of the capillary tubes found no solid materials, but a small amount of precipitated material in the R-134a systems; this substance was identified as a lubricant from a plastic component of the compressors that was investigated before production, deemed tolerable, but since discontinued; compressor calorimeter and noise tests found performance within tolerances; examination of lubricant samples found no significant hydrolysis of the polyolester (POE) used with R-134a, negligible system influence on the water content, and acceptable viscosity; disassembly of the compressors found no signs of wear or copper plating of concern; the paper concludes that both the R-12 and R-134a systems were in excellent condition and that no difference in condition or expected lifetime was found

K. S. Sanvordenker (Tecumseh Products Company), **Materials Compatibility of R-134a in Refrigerant Systems**, *Transactions* (Annual Meeting, Vancouver, BC, 24-28 June 1989), 95(2); republished in ASHRAE Special Publication, *CFCs: Time of Transition,* American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 211-216, January 1989 (6 pages with 5 figures and 1 table, 20 page preprint available from JMC as RDB0001)

Miscibility and pressure-temperature solubility diagrams are presented for R-134a with polyglycol (butyl monoether, polyoxyethylene-propylene, and polyoxypropylene glycol) and polyolester (dibasic acid ester and neopentyl ester) lubricants. The effects of R-134a on two magnet-wire insulations (polyester-imide and polyester enamel overcoated with amide-imide), two unidentified anaerobic adhesives, three elastomeric o-rings (chloroprene, ethylene propylene rubber, and nitrile), and a type 4A molecular-sieve desiccant are addressed. Compressor and refrigerator-freezer tests with R-134a and selected lubricants are described.

S. G. Sundaresan (Copeland Corporation), J. F. Judge, W. Chu, and R. K. Radermacher (University of Maryland), **A Comparison of the Oil Return Characteristics of R-22/Mineral Oil and its HFC Alternatives (R-407C & R-410A) with Mineral Oil and POE in a Residential Heat Pump**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 187-192, July 1996 (6 pages with 7 figures, RDB6920)

steady state, cyclic, and simulated oil pump out tests of R-407C and R-410A with a mineral oil and with a polyolester (POE) lubricant to examine oil return in a 10.6 kW cooling (3 ton) single-speed, split-system heat pump; comparison to R-22 with mineral oil; concludes that R-407C and R-410A have reliable oil return characteristics with POE, but not with the mineral oil

S. G. Sundaresan and W. R. Finkenstadt (Copeland Corporation), **Polyalkylene Glycol and Polyol Ester Lubricant Candidates for Use with HFC-134a in Refrigeration Compressors,** paper AN-92-5-3, *Transactions* (Winter Meeting, Anaheim, CA, January 1992), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 98(1):796-803, 1992 (8 pages with 4 figures and 6 tables, RDB2103)

This paper addresses polyalkylene glycol (PAG) and ester lubricants for use with R-134a in refrigeration compressors, with emphasis on lubricity and materials compatibility. The PAGs include diols (having two free hydroxyl groups), monoethers (one hydroxyl group), and end-capped PAGs (no free hydroxyl groups). The esters include dibasic (DBE), pentaerythritol (PE), trimethylolpropane (TMP), and neopentyl glycol (NPG). Properties of 17 PAG and 22 ester candidates are presented along with miscibility profiles for five of them. Sealed-tube test results are tabulated for four lubricants with

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metals (aluminum, stainless steel, and copper), magnet wire enamel, epoxy, PET film and fiber, polyamide (nylon 6/6), polyimide, polyetherketone (PEK), chloroprene o-ring, and nonasbestos (nitrile binder with clay silicate filler) gasket material. Hygroscopicity and wear from life testing, in semihermetic reciprocating-piston compressors, are summarized. While the exact cause-and-effect mechanisms leading to failure of a connecting rod in one test and wrist pin distress in others have not been established, noticeable differences are reported for the several lubricants. The results indicate that end-capped PAGs and PEs are viable candidates. Esters are preferred over PAGs for retrofit due to their miscibility with hydrocarbon lubricants and compatibility with residual chlorine.

S. G. Sundaresan and W. R. Finkenstadt (Copeland Corporation), **Degradation of Polyethylene Terephthalate Films in the Presence of Lubricants for HFC-134a: A Critical Issue for Hermetic Motor Insulation Systems,** *International Journal of Refrigeration* (IJR), 14(8):317-320, November 1991 (4 pages with 3 figures and 2 tables, RDB2202)

An investigation of polyethylene terephthalate (PET) embrittlement mechanisms with lubricants is summarized. PET is widely used as an insulating material in motors for hermetic compressors. The paper reviews related studies and summarizes both the experimental approach and findings. Degradation was measured after thermal-aging in sealed tubes at 130, 150, and 175 °C (166, 302, and 347 °F) for 7, 14, and 28 days. The effects of drying the PET film and lubricants were evaluated. Three polyalkylene glycols (PAGs) were studied including monol, diol, and end-capped (modified) polypropylene glycols. A pentaerythritol (PE) ester and a blend of PAG-monol and PE-ester also were investigated. All five lubricants were ISO 32 (150 SUS) viscosity for use with R-134a. The effects of moisture content, temperature, and lubricant structure were examined. The results were compared to those of PET in R-12 with mineral oil. The study confirmed earlier findings that PET films must be dried, to less than 0.1% moisture content by weight, to minimize embrittlement by moisture. Residual water in the PET, even after drying, may exceed ten times that contributed by the lubricant and has a greater effect. The extent of embrittlement increases with the number of free hydroxyl groups in PAGs, and neither the monol nor diol was found to be acceptable. The end-capped PAG and ester lubricants showed no adverse reaction with dried PET film.

S. G. Sundaresan and W. R. Finkenstadt (Copeland Corporation), **Evaluation of Polyalkylene Glycol Candidates with HFC-134a in Refrigeration Compressors,** unpublished presentation at ASHRAE's CFC Technology Conference, National Institute of Standards and Technology, Gaithersburg, MD, September 1989 (22 pages with 2 figures and 6 tables, available from JMC as RDB4305)

This paper summarizes miscibility, compatibility, and stability data for R-134a with a series of four unidentified, polyalkylene glycol (PAG) lubricants for refrigeration systems. It also addresses the findings of compressor durability testing with them. The paper outlines both the tests procedures and findings. A table summarizes viscosity, miscibility, moisture content, and acid number measurements; a figure compares the miscibility profiles of the PAGs as functions of temperature and concentration in R-134a. A second table reports the effects of metals on chemical stability of R-134a/lubricant mixtures for two of the PAGs at four moisture levels, both with and without test coupons of aluminum, copper, and steel. No refrigerant or lubricant degradation was detected by gas chromatography or visual appearance, and there was no sign of metal corrosion, rusting, or copper plating. The findings of sealed tube tests at 175 °C (347 °F) are reported for several materials used in system construction. They include magnet wires, polyethylene terephthalate (PET) insulating materials, polyamide (nylon 6,6), polyimide, polyetherketone (PEK), a nitrile-based nonasbestos gasket, and a chloroprene o-ring. Of the findings, the most negative observation involved PAG effects on PET films, attributed both to hydrolysis and alcoholysis (or glycolysis) degradation and to PET embrittlement by hydrolytic cleavage. The paper then reports on tests of lubricity, including both bench and compressor-life tests. The former group included pin and v-block, pin-on-disk, four ball, and other screening tests. The latter comprised a regimen of break-in, normal loading, start/stop, high load, high compression ratio, and flooded start tests. The lubricity and durability findings are tabulated and discussed, noting failures and evidence of component distress for all four PAGs. The authors state that the results are more indicative of early development than of the true potential for R-134a/PAG systems. They conclude that the screening tests have delineated the key issues as: 1) the effects of PAGs on the stability of PET, epoxy varnishes, and polyamide-based polymers, 2) the effects of PAGs on aluminum corrosion and/or wear, and 3) the effects of moisture on PET films and fibers and on aluminum corrosion and/or wear.

S. G. Sundaresan and W. R. Finkenstadt, **Evaluation of Polyalkylene Glycol Candidates with HFC-134a in Refrigeration Compressors,** presentation charts (ASHRAE Annual Meeting, Vancouver, BC, Canada, 24-28 June 1989), Copeland Corporation, Sidney, OH, June 1989 (27 pages with 2 figures and 7 tables, available from JMC as RDB-0529)

Miscibility is shown for 55-100% R-134a with four unidentified polyalkylene glycol (PAG) lubricants (150-180 SUS). Compatibility of the refrigerant-polyglycol mixtures with metals, motor materials, and structural polymers are qualitatively presented. The metals include copper, aluminum, and stainless steel. The motor materials include two magnet-wire insulations (epoxy coated and polyester enamel overcoated with polyamide-imide), a polyethylene terephthalate (PET) slot liner, and an unspecified lead wire insulation. The structural polymers include a chloroprene seal, nonasbestos gasket (nitrile binder and clay silicates as filler), nylon 6/6, polyetherketone (PEK), and polyimide. Effects of the refrigerant-lubricant mixtures on compressor durability were quantitatively reported for test conditions of break-in, normal load, start/stop, high load, high compression ratio, and flooded start.

Y. Takahashi, T. Komatsubara, and T. Sunaga, **Development of Compressor Material Technology for HFC-134a Use**, *Proceedings of the 1994 International Compressor Engineering Conference at Purdue*, edited by W. Soedel, Purdue University, West Lafayette, IN, July 1994 (rdb6915)

R-134a, materials compatibility

R. H. P. Thomas and H. T. Pham (AlliedSignal Incorporated), **Evaluation of Environmentally Acceptable Refrigerant-Lubricant Mixtures for Refrigeration and Air Conditioning,** paper 891967 (Passenger Car Meeting, Dearborn, MI), Society of Automotive Engineers, Warrendale, PA, September 1989 (9 pages with 6 tables and 5 figures, available from JMC as RDB0503)

Laboratory data on the compatibility of R-134a with lubricants and the compatibility of the refrigerant-lubricant mixtures with elastomers and other materials are reviewed. Miscibility of R-134a in three polyglycols, a dihydroxy and two butyl-capped monhydroxy polyalkylene glycols (PAGs), and solubility for R-134a with the first of these are discussed. Stability, dry and with moisture present, also is addressed by comparing copper plating at 149 °C (300 °F) for the systems with R-134a and PAGs to R-12 with mineral oil. Tests of fluoride-ion production in sealed-tube tests, to determine the effects of air and water, are presented. Hose permeability with the refrigerant alone and with the refrigerant-lubricant mixtures, lubricity test using pin and v-block (Falex machine) tests, and swell tests with elastomers are described. The elastomers tested include three nitriles, epichlorohydrin, two neoprenes, a chlorosulfonated polyethylene, and a chlorinated polyethylene. The basic finding is that the combination of R-134a and PAGs is workable.

Compatibility of Elastomers with HFC-134a, report ARTD-5, E. I. duPont de Nemours and Company, Incorporated, Wilmington, DE, 7 November 1989 (16 pages with 12 tables and 1 figure, available from JMC as RDB0538)

This report summarizes an investigation of the compatibility of 11 elastomers at 25, 80, and in some cases at 141 °C (77, 176, and 286 °F) with R-134a. The data presented were taken after 27 days of immersion ("temporary") and also after subsequent drying in air at 25 °C (77 °F) for 14 days ("final"). Comparative data are presented for R-12 immersions under the same conditions. The elastomers also are rated on a scale of 0 ("no change") to 5 ("severe, unacceptable change") based on the "temporary" data. The "final" data are suggested as a guide for seal replacement after equipment tear down. The report outlines the experimental approach and presents a table with the ratings. Eleven subsequent tables present measured changes in length, weight, and Shore A hardness as well as elasticity and visual (both the liquid and the polymer) ratings. The elastomers tested include urethane (Uniroyal Adiprene® C), Buna N and S, butyl rubber, chlorosulfonated polyethylene (DuPont Hypalon® 48), natural rubber, neoprene W, hydrocarbon rubber (DuPont Nordel®), silicone, polysulfide (Morton Thiokol® FA), and fluoroelastomer (DuPont Viton® A). A figure shows the scale used for swell and hardness ratings. The report cautions that the effects of refrigerants on elastomers depend on the nature of the polymer, the compounding formulation used, the curing or vulcanizing condition, the presence of plasticizers or extenders, and other elastomer variables. While the data serve as a guide, generalizations from the results are difficult to make.

Compatibility of Elastomers with HFC-134a and/or Ucon® 50HB660 (RO-W-6602) Plus Additives, report ARTD-18 (H-26845), DuPont Chemicals, Incorporated, Wilmington, DE, 12 July 1990 (16 pages with 12 tables, available from JMC as RDB2112)

This report summarizes an investigation of the compatibility of 11 elastomers at 25 and 80 °C (77 and 176 °F) with a polyalkylene glycol (PAG) lubricant, R-134a, and with a 50/50 refrigerant-lubricant mixture. The data presented were taken after 27 days of immersion ("temporary") and also after subsequent drying in air at 25 °C

please see page 6 for ordering information

(77 °F) for 14 days ("final"). The elastomers also are rated on a scale of 0 ("no change") to 5 ("severe, unacceptable change") based on the "temporary" data. The "final" data are suggested as a guide for seal replacement after equipment tear down. The report outlines the experimental approach and presents a table with the ratings. Eleven subsequent tables present measured changes in length, weight, and Shore A hardness as well as elasticity and visual (both the liquid and the polymer) ratings. The lubricant is identified as Ucon® 50HB660 (RO-W-6602) with a proprietary additive. The elastomers tested include urethane (Uniroyal Adiprene® C), Buna N and S, butyl rubber, chlorosulfonated polyethylene (DuPont Hypalon® 48), natural rubber, neoprene W, hydrocarbon rubber (DuPont Nordel®), silicone, polysulfide (Morton Thiokol® FA), and fluoroelastomer (DuPont Viton® A). The report concludes that R-134a and the tested lubricant have been demonstrated to be an effective combination for automotive air conditioning. It cautions that the effects of refrigerants on elastomers depend on the nature of the polymer, the compounding formulation used, the curing or vulcanizing condition, the presence of plasticizers or extenders, and other elastomer variables. While the data serve as a guide, generalizations from the results are difficult to make.

Compatibility of [H]**FC-134a with Refrigeration System Materials**, report NIST-4, Freon® Products Laboratory, E. I. duPont de Nemours and Company, Incorporated, Wilmington, DE, 14 December 1976 (7 pages with 3 tables, available from JMC as RDB0534)

R-134a

Elastomer Compatibility with HFC-134a: Experimental Details, report NIST-1, Freon® Products Laboratory, E. I. duPont de Nemours and Company, Incorporated, Wilmington, DE, undated circa 1989 (2 pages with 2 tables, available from JMC as RDB0531)

Compatibility tests of elastomers with R-134a and a naphthenic mineral oil (Witco Suniso® 5GS) are summarized. Duplicate samples of two neoprene W samples, National O-Ring and Parker, were exposed for 18 days. Lengths and weights were measured before exposure, immediately after removal, and after storage in ambient air for an additional 15 days. No color change or particulate residue were noted. Temporary and final linear swelling by 4.43-5.76% and 3.07-4.37% was measured. Weight changes of -0.77 to 1.86% were noted upon removal, but they changed to -3.71% to -1.01% after drying.

The Compatibility of Polymeric / Elastomeric Materials with Klea™ 134a and Polyalkylene Glycol (PAG) Based Lubricants, technical note 1, ICI Americas Incorporated, New Castle, DE, USA, August 1990 (8 pages with 5 tables, RDB2515)

Test results are tabulated to summarize changes in weight, volume, length, thickness, strength, elongation to break, and hardness for polymeric and elastomeric materials exposed to refrigerants and lubricants for 14 days. These tests are based on immersions at 130 °C (266 °F) with 50 ppm water for R-12 and mineral oil and at 85 °C (185 °F) with 200 ppm water for R-134a with Emkarox® RL 68 PAG. The materials tested include chloroprene (chlorinated isoprene, neoprene W), chlorinated rubber (neoprene), ethylene propylene diene monomer (EPDM), fluorinated propylene monomer (FPM) copolymer, FPM terpolymer, hydrogenated nitrite (HN) rubber N grade, HN rubber E grade, HN butyl rubber, HN green rubber, natural rubber, nitrile butyl rubber (Buna™ N), butadiene-acrylonitrile copolymer (Buna™ N), nylon 6/6, polybutylene terephthalate (PBT), PBT with 10% glass, polyether ether ketone (PEEK), poly ether sulfone (PES 75), polyethylene terephthalate (PET), polyimide 75 (ICI Upilex® R), polyimide 50 (ICI Upilex® S), polyimide (DuPont Kapton®, poly phenyl sulfone (PPS), and fluorinated copolymer of vinylidene fluoride and hexafluoropropylene (DuPont Viton®). Additional data are provided for R-134a and four PAGs (Emkarox® RL) for EPDM, natural, and nitrile rubbers as well as for nylon, and Viton. These lubricants include a monol PAG ISO 22 with 65 ppm water, modified PAG ISO 22 with 165 ppm water, modified PAG ISO 32 with 190 ppm water, and modified PAG ISO 70 with 85 ppm water. The second set of tests were for thermal aging at 130 °C (266 °F) for 14 days. The experimental approach is briefly outlined.

The Compatibility of Polymeric / Elastomeric Materials with Klea™ 134a and Ester Based Lubricants, technical note 2, ICI Americas Incorporated, New Castle, DE, USA, August 1990 (6 pages with 4 tables, RDB2516)

Test results are tabulated to summarize changes in weight, volume, length, thickness, strength, elongation to break, and hardness for polymeric and elastomeric materials exposed to refrigerants and lubricants for 14 days. These tests are based on immersions at 130 °C (266 °F) with 50 ppm water for R-12 and mineral oil and with 180 ppm water for R-134a with Emkarate™ RL 32S (formerly RLE DE 184). The materials tested include chloroprene (chlorinated isoprene, neoprene W), chlorinated rubber (neoprene), ethylene propylene diene monomer (EPDM), fluorinated propylene monomer (FPM) copolymer, FPM terpolymer, hydrogenated nitrile (HN) rubber N grade, HN rubber E grade, HN butyl rubber, HN green rubber, natural rubber, nitrile butyl rubber (Buna™ N), butadiene-acrylonitrile copolymer (Buna™ N), nylon 6/6, polybutylene terephthalate (PBT), PBT with 10% glass, polyether ether ketone (PEEK), poly ether sulfone (PES 75), polyethylene terephthalate (PET), polyimide 75 (ICI Upilex® R), polyimide 50 (ICI Upilex® S), polyimide (DuPont Kapton®), polyphenyl sulfone (PPS), and fluorinated copolymer of vinylidene fluoride and hexafluoropropylene (DuPont Viton®). Additional data are provided for R-134a and Emkarate™ RL 15S (formerly RLE DE 212) with 180 ppm water for EPDM, natural, and nitrile rubbers as well as for nylon, PBT, and Viton. The experimental approach is briefly outlined.

Polyglycol Sealed-Tube Tests, Carrier Corporation, Syracuse, NY, September 1989 (1 page with 1 table, available from JMC as RDB0021)

A table compares tests of R-12 and R-134a with two polyalkylene glycol (PAG) lubricants (Nippon RS680 and Glygoyle 11). No decomposition was detected for R-134a with either oil. R-12 decomposition was reported at 75-90% with the two lubricants.

UL 984 Tests with R-134a and Oils, Carrier Corporation, Syracuse, NY, undated circa September 1989 (1 page with 1 table, available from JMC as RDB0017)

A table summarizes UL 984 tests of motor materials aged at 110 °C (230 °F) for 60 days. Control results are compared to those after separate exposures to R-12 mixed with mineral oil (Witco Suniso® 3GS) and R-134a mixed with the same oil and with alkylbenzene oil (Zerol® 150). Insulation failures (1 ma current leakage to ground after 1 minute at 1.5 kV) and breakdown voltages are reported. Results are summarized for polyester-imide magnet wire, Dacron-Valox® lead wire, DuPont Teflon® wire sleeving, DuPont Mylar® end cap, Mylar-Dacron® thermosleeve, Mylar® and Melinex® slot liners, and Mylar® and Melinex® phase separators. Breakdown voltages of 0.7-15.5 kV are indicated; current leakage failures resulted only for the polyesterimide magnet wire.

R-717 (Ammonia)

M. Knabe, S. Reinhold, and J. Schenk (Institut für Luft- and Kältetechnik Dresden, ILK, Germany), **Ammoniakanlagen und Kupfer-Werkstoffe?** [Ammonia Systems and Cuprous Materials?], *Ki Luftund Kältetechnik,* Germany, 33(9):394-397, 1997 (4 pages with 5 figures and 4 tables, in German, RDB-9852)

summarizes compatibility tests of copper and copper alloys with ammonia and lubricants in refrigeration systems; tested lubricants included a mineral oil (MO, Shell G68), a polyalkylene glycol (PAG, Reniso PG68), and an unidentified ammonia-miscible, PAG-based lubricant; results with moisture control indicate good stability

H. Lippoid (Institut für Luft- und Kältetechnik Dresden, ILK, Germany), **Kupferwerkstoffe in Ammoniakanlagen** [Cuprous Materials in Ammonia Systems], *KK Die Kälte- und Klimatechnik,* Germany, 50(10):730-735, October 1997 (6 pages with 6 figures and 1 table, in German, RDB9853)

compatibility of copper and copper alloys with ammonia in refrigeration systems

G. D. Short (CPI Engineering Services, Incorporated), **Refrigeration Lubricants Update: Synthetic and Semi-Synthetic Oils Are Solving Problems with Ammonia and Alternative Refrigerants,** *Technical Papers of the 12th Annual Meeting* (Memphis, TN, 4-7 March 1990), International Institute of Ammonia Refrigeration (IIAR), Washington, DC, 19-53, March 1990 (36 pages with 12 figures and 4 tables, available from JMC as RDB2203)

This paper reviews bench tests and field experience with synthetic lubricants. The first part addresses semi-synthetic, high-viscosity index (HVI), hydrocracked lubricants for improved performance with ammonia. These lubricants also are referred to as "hydrocracked paraffinic oils" and as "restructured, semi-synthetic lubricants" to distinguish them from hydrogen finished oils, which contain more aromatic components. The paper discusses the benefits of these lubricants and briefly reviews case histories for two applications. Advantages cited, leading to longer drain intervals, include good thermal and chemical stability, lower mutual solubility, low foaming and volatility, excellent low-temperature fluidity, high viscosity, and good demulsibility. The hydrotreating process also removes nearly all aromatics, including carcinogenic polynuclear aromatics found in some lubricants. The second part addresses polyalkylene glycols (PAGs) and esters in positive displacement compressors for R-134a and refrigerant blends. Previously documented concerns with PAGs and low-viscosity, neopentyl esters are outlined. A new complex ester, which yields improved energy efficiency in screw compressors and superior miscibility with R-22, is discussed. The composition of naphthenic, solvent-refined paraffinic, and hydrocracked paraffinic lubricants are tabulated for comparison. Similar data are provided on oxidation resistance and emulsion characteristics. Plots of viscosity and antioxidant level, as functions of time in use, are provided for the lubricants discussed. Solubility with ammonia, volatility, and viscosity are plotted for the hydrocracked oils. The miscibility of two complex esters are shown for R-134a, and the viscosity-temperature relationships are graphically compared for R-22 with a complex ester and a naphthenic oil. A figure compares the isentropic efficiency of complex esters with R-22 to that for a polyalphaolefin (PAO) lubricant for a range of pressure ratios.

G. D. Short (CPI Engineering Services, Incorporated), **Hydrotreated Oils for Ammonia Refrigeration,** *Technical Papers of the 7th Annual Meeting* (10-13 March 1985, San Antonio, TX), International Institute of Ammonia Refrigeration (IIAR), Washington, DC, 149-176, March 1985 (28 pages with 8 figures and 4 tables, available from JMC as RDB2204)

R-717, lubricants

Others

P. E. Hansen, A. Riemer, and J. Bachmann (Danfoss Compressors GmbH, Germany), **Physical and Chemical Stability of Hermetic Systems Using R600a and R290**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:820-824, 1995 (5 pages with 2 figures and 4 tables, rdb-6C32)

R-290 (propane), R-600a (isobutane), R-290/-600a (50/50), materials compatibility, reliability of hermetic systems with hydrocarbons: no signs of mechanical thermal degradation were found in the refrigerant or lubricant (an unidentified mineral oil) after 8,000 hr of accelerated test; compressor wear was deemed acceptable

S. Takubo (Research Institute of Innovative Technology for the Earth, RITE, Japan), Y. Mochizuki (RITE), and A. Sekiya (National Institute of Materials and Chemical Research, NIMC, Japan), **Thermal Stability of HFE-245mc as a Refrigerant of the Next Generation**, *Reito* [Refrigeration], Japan, 73(847):11-14 also numbered 417-420, May 1995 (4 pages with 4 tables in Japanese with English summary, RDB8702)

thermal stability tests of R-E245cb1 ("HFE-245mc") at 125, 150, and 175 °C (257, 302, and 347 °F) for 10, 30, and 60 days in sealed glass tubes; concludes that R-E245cb1 is sufficiently stable for use as a refrigerant despite formation of "minute" amounts of methyl trifluoroacetate (MTFA, $CH_3CO_2CF_3$); indicates that prototype testing in a Beat pump is underway

Blends

Y. Obokata, M. Hagiwara, and T. Komatsubara (Sanyo Electric Company, Limited, Japan), **Reliability Study on a Rotary Compressors for HFC Refrigerants Mixture,** paper 6.3, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 145-149, December 1994 (5 pages with 12 figures and 8 tables; in Japanese with abstract, figures, and tables in English; RDB5427)

R-22, R-32, R-125, R-134a, and R-407C; alkylbenzene, polyolester, and carbonate lubricants, compatibility

R. H. P. Thomas and R. Robinson, **The Solubility of Air in HFC Refrigerants,** unpublished presentation (ASHRAE Annual Meeting, San Diego, CA, 24-28 June 1995), AlliedSignal Incorporated, Buffalo, NY, June 1995 (9 pages with 4 figures, available from JMC as RDB5701)

This set of presentation charts addresses the effects of air as a refrigerant contaminant, with emphasis on hydrofluorocarbon (HFC) refrigerants. The introduction indicates that air raises the system pressure, reduces efficiency, causes oxidation of lubricants and metallic components, and interacts with water to enhance reactions. A figure schematically shows a vessel with gas and liquid sample cylinders and a stirrer, used to measure pressure variations. A plot illustrates the variation of pressure with air concentrations of 0-4% at 10 and 20 °C (50 and 68 °F); the influence is more pronounced at the higher temperature. A chart notes an earlier study by H. M. Parmelee in 1951. It found the solubility of air to obey Henry's Law for R-12 and R-22, with similar solubility coefficients. A plot combines new data for R-134a with Parmelee's for R-12 and R-22. It suggests that the solubility coefficient is a linear or near-linear function of temperature. The authors conclude that chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC), and HFC refrigerant behave similarly with respect to air, based on the three representative refrigerants. They also show more detailed data for R-507A, and conclude that it behaves like a single-compound refrigerant with regard to air solubility. AlliedSignal's product name for R-507A is Genetron® AZ-50.

Measurement of Solubility, Viscosity, and Density of R-32/125 (R-410 Series) Refrigerant-Lubricant Mixtures, research project 928-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, September 1997 - December 1997, extended to 1998 (ASH0928)

This project will investigate the solubility, viscosity, and density of R-410A with polyolester (POE) lubricants for -40 to 125 °C (-40 to 257 °F). The contractor for the project was Imagination Resources, Incorporated (IRI), led by R. C. Cavestri; it is sponsored by ASHRAE Technical Committees 8.1, *Positive Displacement Compressors,* and 3.4, *Lubrication.*

Water Solubility in HFC Refrigerant Blends, research project 923-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1996 - November 1997, extended to 1998 (ASH0923)

This project will measure the solubility of water in R-23, R-32, R-125, R-143a, and R-152a at temperatures of -73 to 71 °C (-100 to 160 °F), or 8 °C (15 °F) below the critical temperature. It also will investigate the solubility of water in mixtures of these compounds and verify the projections with measurements on three or more ternary blends of them. The contractor for the project is Imagination Resources, Incorporated (IRI), led by R. C. Cavestri; it is sponsored by ASHRAE Technical Committee 3.3, *Contaminant Control in Refrigerating Systems.*

LUBRICANTS AND TRIBOLOGY

A. Bayini (École Polytechnique Fédérale de Lausanne, ÉPFL, Switzerland), J. R. Thome (Engineering Consultant), and D. Favrat (ÉPFL), **On-Line Measurement of Oil Concentrations of R-134a/Oil Mixtures with a Density Flow Meter**, *HVAC&R Research,* 1(3):232-241, 1995 (10 pages with 5 figures and 1 table, rdb7637)

measurements of lubricant concentrations in circulating R-134a using a high accuracy, density flow meter of the straight vibrating tube type: measurements for calibrated concentrations of 0-6% oil by mass over the range from -9.4 to 5.9 °C (15-43 °F) were correlated to the density, temperature, and liquid compressibility with an average error of 0.09% by mass, with a 95% confidence limit of 0.21%; a simplified method, not requiring calibration tests, was developed for industrial application of the density flow meter to any refrigerant-lubricant (RL) mixture combination; the method yields an average error of 0.22% by mass with a 95% confidence limit of 0.67%

F. R. Biancardi, D. R. Pandy, T. H. Sienel, and H. H. Michels (United Technologies Research Center, UTRC), **Study of Lubricant Circulation in HVAC Systems,** presentation (ASHRAE Winter Meeting, Philadelphia, PA, 25-29 January 1997), report DOE/CE/23810-82A, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 29 January 1997 (28 pages with 19 presentation charts including 6 figures and 4 tables, available from JMC as RDB7210)

A narrative summary and presentation charts summarize a study of lubricant movement for R-407C with two mineral oil (MO, Witco Suniso® 1GS and 3GS) and two branched acids polyolester (Castrol Icematic® SW32 and SW68) lubricants. R-22 also was tested with the MO (3GS) for comparison. The charts describe a dynamic test facility, used to measure flow and oil movement in a split system, residential heat pump in both the cooling and heating modes. The charts introduce the project, summarize miscibility data for the tested fluids, describe the test facility and its operating range, discuss the instrumentation used, and explain circuiting features used to allow a range of flow conditions. Two charts illustrate the data taken, and a table summarizes oil return problems found and potential causes. A further table summarizes the minimum flow velocities with and without oil return problems. Concluding charts present the conclusions and recommendations. The flow velocity at which the worst-case lubricant management was found was approximately 0.5 m/s (100 ft/min) for heating. Minimum flow velocities of 1.8-1.9 m/s (350-375 ft/min) were required for cooling. An unexpected finding was that R-407C exhibited good, if not better, oil return with the immiscible MO lubricants and could operate with even lower flow velocities. See RDB6C04 for further information on this study.

F. R. Biancardi, H. H. Michels, T. H. Sienel, and D. R. Pandy (United Technologies Research Center, UTRC), **Study of Lubricant Circulation in HVAC Systems**, report DOE/CE/23810-71 volume 1, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, October 1996 (80 pages with 28 figures and 14 tables, available from JMC as RDB6C04)

This report introduces, describes the test facility, summarizes results, and recommends further research for an experimental and analytical study to determine lubricant circulation characteristics. R-407C was tested as a representative hydrofluorocarbon (HFC) refrigerant with two mineral oil (MO, Witco Suniso® 1 GS and 3GS) and two branched acids polyolester (Castrol Icematic® SW32 and SW68) lubricants. R-22 also was tested with the MO (3GS) for comparison. The report describes a dynamic test facility to measure performance, flow, and oil movement in a split system, residential heat pump in both the cooling and heating modes. The report reviews available data on the miscibility of refrigerants and lubricants and on oil return practices. It then presents the design of the test apparatus and instrumentation, data collection and analysis, test results, conclusions, and recommendations. The flow velocity at which the worst-case lubricant management was found was approximately 0.5 m/s (100 ft/min) for heating, for which low oil concentrations of 0.25-0.5% are normal. Minimum flow velocities of 1.8-1.9 m/s (350-375 ft/min) were required for cooling. The report recommends these velocities as the minimums for oil return, and notes that R-22 and R-407C require approximately the same minimum velocities with miscible refrigerants. An unexpected finding was that R-407C exhibited good, if not better, oil return with the immiscible MO lubricants and could operate with even lower flow velocities. See RDB6C05 for test data.

F. R. Biancardi, H. H. Michels, T. H. Sienel, and D. R. Pandy (United Technologies Research Center, UTRC), **Study of Lubricant Circulation in HVAC Systems**, report DOE/CE/23810-71 volume II, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, October 1996 (150 pages with 132 figures and 1 table, available from JMC as RDB6C05)

This report contains the test data as taken from laboratory tests for a study to determine lubricant circulation characteristics. A table summarizes the test runs, and two schematics show the cooling and heating mode operation and instrumentation points. The data cover tests of R-407C with two mineral oil (MO, Witco Suniso® 1 GS and 3GS) and two branched acids polyolester (Castrol Icematic® SW32 and SW68) lubricants. R-22 also was tested with the MO (3GS) for comparison. The tests measured the flow velocities and oil movement in a split system, residential heat pump in both the cooling and heating modes. See RDB6C04 for a description of the tests, discussion of results, conclusions, and recommendations.

J. Bougard and R. Jadot (Polytechnique de Mons , France), **Modelisation des Équilibres Réfrigérant-Huile** [Modeling of Refrigerant-Oil Equilibria], *Energy Efficiency and Global Warming Impact* (proceedings of the meetings of Commissions B1 and B2, Ghent, Belgium 12-14 May 1993), International Institute of Refrigeration (IIR), Paris, France, 149-156, 1993 (8 pages with 9 figures and 1 table, in French, RDB531 1)

R-22 with mineral oil and unidentified synthetic lubricant, R-134a with polyalkylene glycol (PAG) lubricant, solubility, vapor pressure

P. D. Brechot, J. C. Remigy (Research Centre of Mobil Oil Française, France), K. J. Buzdygon, and G. J. Johnston (Mobil Research and Development Corporation, USA), **Refrigeration Oils for Systems Operating with Ozone-Friendly Refrigerants: Key Rig Performance and Field Applications,** *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:96-104, 1995 (9 pages with 9 figures and 6 tables, rdb7730)

review of the miscibility, antiwear, and hydrolytic properties of a range of polyolester (POE) lubricants for use with hydrofluorocarbon (HFC) and hydrocarbon (HC) refrigerants: representative properties for neopentylglycol (NPG), trimethylol-propane (TMP), pentaerythritol (PE), and dipentaerythritol (DPE), esters; influence of acid and alcohol structure on miscibility and viscosity; laboratory tests of compressors in a test rig with examination of aluminum, copper, silicon, and sodium deposits on filter driers; field retrofit tests of R-134a with POE lubricants for R-12 and naphthenic mineral oils (MO) in centrifugal and reciprocating piston chillers, R-402A with POE for R-502 with an alkylbenzene (AB) oil; and R-404A with POE for R-404A with MO and AB MO lubricants with differing flushing approaches; comparison of MO, poly alphaolefin POE, and a diester with R-600a in hermetic compressors; concludes that synthetic lubricants may offer advantages

M. Burke, S. Carre, and H. H. Kruse (Universität Hannover, Germany), **Oil Behavior of the HFCs R32, R125, and R-134a and One of Their Mixtures**, *CFCs, the Day After* (proceedings of the IIR meeting, Padova, Italy, 21-23 September 1994), International Institute of Refrigeration (IIR), Paris, France, 89-98, September 1994 (10 pages, rdb8429)

refrigerant-lubricant properties for R-32, R-125, and R-134a

M. Burke and H. H. Kruse (Universität Hannover, Germany), **Solubility and Viscosity of New Oil-Ammonia Systems,** *Energy Efficiency and Global Warming Impact* (proceedings of the meetings of Commissions B1 and B2, Ghent, Belgium 12-14

May 1993), International Institute of Refrigeration (IIR), Paris, France, 133-139, 1993 (7 pages with 4 figures and 1 table, RDB5309)

R-717, polyolester (POE), polyalkylene glycol (PAG), ethylene oxide (EO) and propylene oxide (PE) compositions, additives

M. Burke and H. H. Kruse (Universität Hannover, Germany), **Das Ölverhalten der chlorfreien Kältemittel R23, R134a, and R152a** [Oil Retention in Chlorine-Free Refrigerants R-23, R-134a, and R-152a], *Ki Klima-Kälte-Heizung,* Germany, 19(9):348-351, September 1991 (4 pages in German, rdb4531),

refrigerant-lubricant miscibility

R. C. Cavestri (Imagination Resources, Incorporated, IRI), **Compatibility of Lubricant Additives with HFC Refrigerants and Synthetic Lubricants** (Final Report, Part 1), report DOE/CE/23810-76, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, July 1997 (74 pages with 9 tables, available from JMC as RDB7703)

results of a literature search and discussion of lubricant additives; lists sources, functional properties, and chemical data for additives; focus includes antioxidant, antiwear, antifriction, antisieze, antimalfunction additives as well as corrosion inhibitors and stabilizers for synthetic, polyolester (POE) lubricants; discusses the modes of action, additive chemistry, and thermal stability for additives used in refrigeration compressor lubricants

R. C. Cavestri (Imagination Resources, Incorporated, IRI), **Potentially Useful Polyolester Lubricant Additives. An Overview of Antioxidants, Antiwear and Antisieze Compounds**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 169-174, July 1996; republished as report DOE/CE/23810-72D, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 1996 (10 pages, available from JMC as RDB-6835)

results of a literature search; discussion of additives known to be used in refrigeration compressor lubricants, their modes of action, additive chemistry, thermal stability; antioxidant, antiwear, and antisieze additives for synthetic, polyolester (POE) lubricants

R. C. Cavestri (Imagination Resources, Incorporated, IRI), **Viscosity, Density, and Gas Solubility of Refrigerant Blends and Azeotropes in Selected Refrigerant Lubricants**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 413-418, July 1994 (6 pages with 12 figures, RDB4855)

R-404A [R-125/143a/134a (44/52/4)], R-507A [R-125/143a (50/50)], polyolester branched acid, polyolester mixed acid

R. C. Cavestri, J. Munk, and M. Menning (Imagination Resources, Incorporated, IRI), **Solubility, Viscosity, and Density Measurements of Refrigerant-Lubricant Mixtures - Part I: Branched Acid Pentaerythritol Polyolesters with R-134a**, paper 3804 (716-RP), *Transactions* (Annual Meeting, Orlando, FL, 25-29 June 1994), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 100(2):220-230, 1994 (11 pages with 11 figures, RDB4716)

This paper presents data on the equilibrium gas solubility, viscosity, and density of R-134a in branched acid, pentaerythritol polyolester (POE) lubricants. It covers dissolved gas ranges of 2% to more than 65% by weight for pressures up to 3445 kPa (500 psia). The two lubricants tested were 32 and 100 ISO viscosity grade POEs (Henkel Emery® 2927-A and Castrol Icematic® SW-100). The paper reviews prior research of refrigerant-lubricant properties, noting that little is known about the hydrodynamic lubricant film-forming qualities of synthetic lubricants with refrigerant mixtures. It describes and schematically illustrates the oscillating-body viscometer used. This apparatus accurately determines density as well as viscosity, under identical elevated pressure and temperature conditions. Two pairs of figures present smoothed viscosity and pressure data, in modified Daniel plots, and density and pressure data for temperatures of -25 to 125 °C (-13 to 257 °F) for the two viscosity grades. Additional plots show the miscibility ranges of R-134a with the 100 ISO POE as well as the isothermal viscosity, and concentration curves for each lubricant at 40 and 100 °C (104 and 212 °F). A final plot shows the kinematic viscosities of both lubricants for the same temperature range. The paper notes that the relative viscosity change with 10% refrigerant dilution is dramatic for the 32 ISO lubricant.

R. C. Cavestri, J. Munk, and M. Menning (Imagination Resources, Incorporated, IRI), **Solubility, Viscosity, and Density Measurements of Refrigerant-Lubricant Mixtures - Part III: Polyalkylene Glycols with R-134a**, paper 3805 (716-RP), *Transactions* (Annual Meeting, Orlando, FL, 25-29 June 1994), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 100(2):231-238, 1994 (8 pages with 11 figures, RDB4717)

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This paper presents data on the equilibrium gas solubility, viscosity, and density of R-134a in polyalkylene glycol (PAG) lubricants. It covers dissolved gas ranges of 1% to more than 70% by weight for pressures up to 3445 kPa (500 psia). The two lubricants tested were a 32 ISO viscosity grade, polypropylene glycol monobutyl ether (ICI Emkarox® VG32) and an 80 cSt, polyoxypropylene diol (Dow Chemical P1200). The paper briefly outlines the experimental approach used and presents plots based on fits of the measured data to an equation of state. Two pairs of figures present viscosity and pressure data in modified Daniel plots along with and density and pressure data for the two PAGs. These plots cover temperatures of -25 to 125 °C (-13 to 257 °F). The paper discusses the enhancements made to the conventional form for the Daniel charts. Additional plots show the miscibility ranges of R-134a and the isothermal viscosity and curves for each lubricant. A final plot shows the kinematic viscosities of both lubricants for the same temperature range.

R. C. Cavestri (Imagination Resources, Incorporated, IRI), **Measurement of Viscosity, Density, and Gas Solubility of Refrigerant Blends in Selected Synthetic Lubricants**, report DOE/CE/23810-46, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 15 May 1995 (198 pages with 192 figures and 20 tables, available from JMC as RDB5603)

This report summarizes measurements of viscosity, density, and solubility for mixtures two 32 ISO VG, polyolester (POE) lubricants with three refrigerant blends and with the components of those blends. They included R-32, R-125, R-134a, R-143a, R-404A, R-407C, and R-507A. They were tested with branched- and mixed-acid POEs (Henkel Emery® 2968A and ICI Emkarate™ RL 32S, respectively). Data on R-22 and R-502 with a naphthenic mineral oil (MO, Witco Suniso® 3GS) are included for comparison. The report describes the measurement methods and schematically illustrates the oscillating body viscometer, blend sampling apparatus, and hydraulic cylinder (to assure uniform composition) used. The results for each refrigerant-lubricant pair are summarized with three figures. They show viscosity as a function of temperature for representative isobars, viscosity and pressure at constant concentrations as functions of temperature in modified Daniel plots, and density as a function of temperature at constant concentrations. Each series is supported by an appendix that contains a table of raw viscosity, density, and solubility data as well as plots of the viscosity and gas solubility at representative temperatures. Gas fractionation also is shown for the blends. Additionally, the plots for R-407C are repeated with and without use of the zero-head, hydraulic injection cylinder; it was introduced to minimize composition changes with successive sampling from a single container. The report findings show the reduction in lubricant viscosity due to gas dissolved in the lubricant. An appendix describes selection of the fluids based on miscibility evaluations for R-32/125 (60/40), R-32/125/134a (30/10/60), R-32/125/290/134a (20/55/5/20), R-32/134a (30/70), R-125/143a (45/55), and R-404A. Their miscibilities are plotted for five lubricants, including two branched-acid POEs (Castrol Icematic® SW32 and Henkel Emery® 2968a), two mixed-acid POEs (ICI Emkarate™ RL 32S and Mobil Arctic® EAL 224R), and an alkylbenzene (AB, Shrieve Zerol® 150).

R. C. Cavestri (Imagination Resources, Incorporated, IRI), **Measurement of the Solubility, Viscosity, and Density of Synthetic Lubricants with R-134a,** final report for 716-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 17 April 1993 (72 pages with 58 figures and 4 tables, RDB4618)

This report presents data on the equilibrium gas solubility, viscosity, and density of R-134a in synthetic polyolester (POE) and polyalkylene glycol (PAG) lubricants. It covers dissolved gas ranges of 2% to more than 65% by weight for temperatures of -25 to 125 °C (-13 to 257 °F) and pressures up to 3445 kPa (500 psia). The POEs tested included 32 and 100 ISO VG branched acid, pentaerythritols (Henkel Emery® 2927-A and Castrol Icematic® SW-100). The PAGs were a 32 ISO viscosity grade, polypropylene glycol monobutyl ether (ICI Emkarox® VG32) and an 80 cSt, polyoxypropylene diol (Dow Chemical P1200). The introduction briefly reviews the role of lubricants, noting that little is known about the hydrodynamic lubricant film-forming qualities of synthetic lubricants with refrigerant mixtures. It also reviews prior research of refrigerant-lubricant properties. The report then describes the oscillating-body viscometer used, provides a schematic for it, and details the experimental procedures. This apparatus accurately determines density as well as viscosity, under identical elevated pressure and temperature conditions. The pressure-viscosity-temperature relationships are presented for R-134a with each lubricant at its individual isothermal measurement temperatures. These modified Daniel plots detail the composition of the equilibrium gas solubility, vapor pressure, concentration, and viscosity in both metric (SI) and inch-pound (IP) units of measure. An appendix shows the miscibility ranges of R-134a with the 100 ISO POE and the two PAGs. A second appendix presents plots of the kinematic viscosities of both lubricants. Four final appendices show the isothermal viscosity and concentration curves and tabulate the raw data for measurements at -25, -15, -7, 0, 20, 40, 60, 80, 100, and 125 °C (-13, 5, 19, 32, 68, 104, 140, 176, 212, and 257 °F).

Y. N. Chang and A. Nagashima, **Effect of Dissolved Lubricating Oils on the Viscosity of Alternative Refrigerants,** *International Journal of Thermophysics,* 14(5):1007-1019, 1993 (13 pages, rdb7638)

refrigerant-lubricant mixture properties

I. G. Chumak, V. P. Chepurnenko, V. P. Onischenko, V. P. Zhelezny, and M. M. Dets (Odessa State Academy of Refrigeration, Ukraine), **Systems of Cooling on Mixtures Containing Ammonia with a Soluble Oil**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:667-670, 1995 (4 pages with 1 figure and 1 table, rdb-7910)

thermophysical properties of a new synthetic lubricant, XMPA-1, that is miscible with R-717 (ammonia); tests with R-717 in a domestic refrigerator using a hermetic compressor

S. Corr, S. Randles, and A. Stewart (ICI Chemicals and Polymers, Limited), **Synthetic Lubricants for R134a - A Replacement Gas for R12**, Lubricants of the Future and Environment, Brussels, September 1993 (rdb5124)

R-12, R-134a

S. Corr, F. T. Murphy (ICI Chemicals and Polymers, Limited), B. E. Gilbert, and R. W. Yost (ICI Americas, Incorporated), **Characteristics of Refrigerant Lubricant Mixtures Containing R-32 and R-32 Blends**, paper DE-93-20-1, *Transactions* (Annual Meeting, Denver, CO, June 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(2):1123-1128, 1993 (6 pages with 5 figures and 3 tables, RDB3624)

S. Corr, P. D. Guy, A. A. Lindley, F. T. Murphy, G. Tompsett (ICI Chemicals and Polymers, Limited), and T. W. Dekleva (ICI Americas, Incorporated), **The Effect of Miscibility on Performance of R-134a and Alternative Lubricants**, seminar presentation at the ASHRAE Annual Meeting (Indianapolis, IN), ICI Americas Incorporated, New Castle, DE, 24 June 1991 (20 pages with 24 charts, RDB2521)

S. Corr (ICI Chemicals and Polymers, Limited), **Solubility and Miscibility - Relevance to Klea™ 134a Refrigeration Systems**, ICI Americas Incorporated, Wilmington, DE, USA, 8 February 1991 (11 pages with 8 figures, RDB2520)

This document explains the meaning and relevance of solubility and miscibility within refrigeration systems. It notes that the solubility of refrigerant gas in the lubricant usually is an important lubricant feature. In general, lubricants that display miscibility with the refrigerant liquid over a wide range of conditions will also have good refrigerant gas solubilities, but the reverse is not necessarily true. Although the solubility of refrigerant gas in liquid lubricant is important in determining the viscosity of fluid at the evaporator outlet, other factors also are likely to have an effect. An example is the lubricant structure (e.g., polarity or hydrogen bonding). The viscosity of the circulating liquid phase and the velocity of the driving gas are the two most important considerations for lubricant return to the compressor. Lubricant viscosity and the solubility-related viscosity of the refrigerant-lubricant mixture would be expected to govern lubricant holdup, a measure of the lubricant quantity available to interfere with heat transfer. Experience indicates that the concentration of lubricant in the liquid refrigerant phase is below 1% over the majority of the evaporation process, so lubricant miscibility actually does not appear to be significant in determining oil holdup. Separate liquid phases for the refrigerant and lubricant will be present only over a very short length of the evaporator. Plots and tabular data are provided for low-temperature miscibility for ester lubricants (Emkarate™ RL) in R-134a. The fraction of lubricant in refrigerant also is plotted for the evaporator length.

K. E. Davis and J. N. Vinci (Lubrizol Corporation), **Formulation of Polyol Ester Lubricants for Use with HFC Refrigerants**, paper 1.3, *Proceedings of the International Seminar on New Technology of Alternative Refrigerants - Lubricants and Materials Compatibility* (Tokyo, February 1993), Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 15-20, February 1993 (6 pages with 9 tables, RDB3308)

polyolester

K. E. Davis and J. N. Vinci (Lubrizol Corporation), **Effect of Additives in Synthetic Ester Lubricants Used with HFC-134a Refrigerant**, *Proceedings of the International CFC and Halon Alternatives Conference* (Washington, DC), Alliance for Responsible CFC Policy, Arlington, VA, 125-133, September 1992 (9 pages with 5 figures); reprinted by Lubrizol Corporation, Wickliffe, OH, 1992 (20 pages with 5 figures, RDB2A08)

This paper reviews tests of antiwear additives with synthetic ester lubricants, for use with R-

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134a in automotive and stationery compressors The lubricants addressed are polyol-carboxylic acid condensation products. The additive screening and tests focused on suitability fog wear protection of aluminum on steel, steel or steel, and bronze on steel. The advantages of R-12 lost in conversion to R-134a are outlined they include inherent antiwear properties, associated with formation of metal-chloride boundary layers, and miscibility with mineral oils. The R-134a advantages, specifically avoidance of ozone depletion and high relative stability, also are noted. A need for a balanced additive approach, respecting both protection of contacting surfaces and low aggressivity toward copper and aluminum design components, is cited The paper notes that the issue of copper plating is a selection constraint, in light of its prominence with R-134a and use of polar, potentially active lubricants. The paper reviews a screening protocol based on Falex pin and v-block tests. Results are plotted for R-12 with mineral oil, R-134a with the ester, and the latter pair with six unidentified additive systems. The most promising of the additive packages was further tested with three polyolester lubricants for viscosities of 15-130 cSt. This additive is described as carefully balanced for multi-metal compatibility, namely sufficiently active for anti-wear protection yet relatively inactive toward aluminum and copper-containing components The findings of the compressor tests, including visual examination for distress, deposit formation, and copper plating are reviewed. A figure qualitatively compares the Falex and compressor results. The figure show the Falex test to be a good predictor, though it indicates greater bronze-on-steel concern for the optimized additive than was experienced in the compressor tests.

D. L. Dick, J. N. Vinci, K. E. Davis, G. R. Malone, and S. T. Jolley, **Polyol Ester Interactions with Additives and Desiccants,** Lubrizol Corporation, Wickliffe, OH, 1996 (5 pages with 2 figures, available from JMC as RDB6902)

This paper presents experiments to investigate factors that govern polyolester (POE) lubricant stability. It also discusses stabilization of additized POEs at extreme temperatures. Duplicate sealed-tubes containing the lubricant specimens were aged at 130 or 180 °C (266 or 356 °F) for 1-3 weeks. The samples then were assayed for water, via the Karl Fischer method, and total acid number (TAN). The lubricants comprised *conventional* and *hindered* base esters, formulated esters, and each of them with an antiwear additive, a hydrolysis inhibiting agent, and both of these additives. Plots compare the hydrolytic stability of the unadditized and five formulated POEs alone, with added desiccant, with the hydrolysis inhibitor, and with the desiccant and inhibitor for both *conventional* and *hindered* POEs. The paper presents the sample preparation, test procedures, and discussion of the results. It concludes that the *hindered* POE is more resistant to hydrolysis than the conventional counterpart, even with additives present. Further, both the molecular sieve desiccant and hydrolysis inhibiting chemical markedly enhance the stability of unadditized and additized lubricants. Their combined effect produced a substantial enhancement, particularly for the hydrolytically less stable, *conventional* POE. While the paper shows differences in hydrolysis potential among the different formulations, the desiccant-inhibitor combination held acidity to very low levels with all of the additives tested.

F. Espinoux, G. Bardy, B. Constans, P. Sanvi, and N. Genet (Elf Centre de Recherche de Solaize, France), **Lubricity Evaluation for Lubricants Used in Refrigeration with HFC-134a,** *Proceedings of the 1992 International Refrigeration Conference - Energy Efficiency and New Refrigerants,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 2:405-414, July 1992 (10 pages with 6 figures and 3 tables, RDB2823)

R-134a

M. Fukuta, T. Yanagisawa, T. Shimizu, and H. Nishijima (Shizuoka University, Japan) **Transient Mixing Characteristics of Refrigerant with Refrigeration Oil,** *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:215-222, 1995 (8 pages with 16 figures and 2 tables, rdb7807)

R-22 with a naphthenic mineral oil (MO, Witco Suniso® 3GS, 4GS, and 5GS), refrigerant-lubricant properties, viscosity, foaming

K. F. Fung (Tyler Refrigeration Corporation) and S. G. Sundaresan (Copeland Corporation), **Study of Oil Return Characteristics in a Display Case Refrigeration System - Comparison of Different Lubricants for a HFC-Blend Refrigerant**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 121-128, July 1994 (8 pages with 4, figures and 6 tables, RDB4815)

R-404A, R-502, naphthenic mineral oil, polyolester

V. Z. Geller (Thermophysics Research Center), A. Yokozeki, and D. B. Bivens (DuPont Chemicals), **Solubility and Viscosity of Alternative Refrigerant/Lubricant Oil Mixtures**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 59-67, October 1995 (9 pages with 5 figures and 3 tables, available from JMC as RDB5A46)

R-32, R-125, R-410B, polyolester (POE) lubricant, vapor pressure, density, viscosity

V. Z. Geller (Thermophysics Research Center) and K. E. Davis (Lubrizol Corporation), **Solubility and Viscosity of Refrigerant/POE Lubricant Mixtures**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:223-229, 1995 (7 pages with 6 figures, RDB7808)

R-32, R-134a, R-404A, R-407C, R-410A or R-410B, and R-507A, polyolester (POE) lubricant, vapor pressure, density, fluidity, viscosity, viscometer

V. Z. Geller, M. E. Paulaitis (University of Delaware), D. B. Bivens, and A. Yokozeki (DuPont Fluoroproducts), **Viscosities for R22 Alternatives and Their Mixtures with a Lubricant Oil**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 49-54, July 1994 (6 pages with 3 figures and 5 tables, RDB4809)

R-32, R-125, R-134a, R-143a, polyolester lubricant

V. Z. Geller, M. E. Paulaitis (University of Delaware), D. B. Bivens, and A. Yokozeki (DuPont Chemicals), **Viscosity of HFC-32 and HFC-32/Lubricant Mixtures,** *Preprints of the 12th Symposium on Thermophysical Properties* (Boulder, CO, 19-24 June 1994), American Society of Mechanical Engineers (ASME), New York, NY, 477-486, June 1994; republished in the *International Journal of Thermophysics*, Plenum Publishing Corporation, Brugge, Belgium, 17(1):75-88, 1996 (10/14 pages, rdb5B25)

R-32, lubricants, properties

W. C. Gergel, **Lubricant Additive Chemistry,** Lubrizol Corporation, Wickliffe, OH, 21 January 1992 (16 pages with 27 figures and 7 tables, RDB3906)

This bulletin reviews the market for, functions of, and types of lubricant additives. It covers diverse applications, but portions also apply to air conditioning and refrigeration. The document summarizes consumption statistics for formulated lubricating oils, noting total annual demand of 34 million metric tons on a worldwide basis. It also discusses uses and the specifications set for key applications. It presents lubricant functions, including contaminant containment, heat removal, and friction reduction. It then discusses additive types including detergents, dispersants, inhibitors, pour point depressants, foam inhibitors, and viscosity modifiers. It also reviews additive types used in automotive transmissions as well as industrial oils and associated additive groups.

C. Gillet-Ducruet, B. Hivet, A. Marion, and M. Churpin (Éectricé de France, ÉDF, France), **Étude de la lubrification d'un compresseur bivis sur une installation au R404A** [Study of the lubrication of Twin-Screw Compressor Using R-404A], *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:797-804, 1995 (8 pages with 4 figures and 1 table, in French, rdb7921)

conversion of an open, Bitzer screw compressor from R-502 with an alkylbenzene (AB, Barelf AL 100) lubricant to R-404A with a polyolester (POE, Planetelf ACD 100 LT) lubricant: experimental conditions; solubility with attention to the influences of pressure, temperature, and superheat; viscosity; concludes that the solubility of R-404A in the POE lubricant varies from 12 to 13% depending on conditions and that the resulting viscosity of the refrigerant-lubricant mixture exceeds 11 cSt; no degradation of the lubricant was found after 2,000 hr of operation

D. Y. Goswami, D. O. Shah, C. K. Jotshi, S. S. Bhagwat, M. Leung, A. S. Gregory, and S. Lu (University of Florida), **Foaming Characteristics of Refrigerant/Lubricant Mixtures**, report DOE/CE/-23810-88, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, March 1998 (190 pages with 80 figures and 21 tables, available from JMC as RDB8701)

This report examines the rate of absorption of refrigerants by lubricants, the rate at which the refrigerant is desorbed following a pressure drop, and the foaming characteristics of the refrigerant-lubricant (RL) mixture as the refrigerant leaves the solution. It presents measured absorption and desorption rates of R-32, R-125, R-134a, R-143a, R-404A, R-407C, and R-410A in polyolester (POE) lubricants (Witco Suniso® SL68 and ICI Emkarate™ RL68H). It provides comparative data for R-12 and R-22 with a naphthenic mineral oil (MO, Witco Suniso® 3GS and 4GS) for comparison. The report also presents viscosity, static and dynamic (interfacial) surface tension, foamability, and foam stability data for the nine refrigerant-lubricant (RL) pairs. The document reviews of prior pertinent publications and describes the experimental approach and apparatus. The report concludes that slow absorption rates correspond to a smaller reduction in surface tension, lower foamability, and higher desorption rate. The R-134a/POE pair is an example of a mixture with a

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fast absorption rate and slow desorption rate, while R-143a/POE exemplifies slow absorption and rapid desorption. The report also concludes that the foamability and foam stability for HFC/POE mixtures are lower than for R-12 or R-22 with mineral oil.

D. Y. Goswami, D. O. Shah, C. K. Jotshi, S. S. Bhagwat, M. Leung, and A. S. Gregory (University of Florida), **Foaming Characteristics of HFC Refrigerants**, *ASHRAE Journal*, 39(6):39-40 and 42-44, June 1997 (5 pages with 2 figures and 1 table, RDB7635)

absorption and desorption rates of R-32, R-125, R-134a, R-143a, R-404A, R-407C, and R-410A in polyolester (POE) lubricants (Witco Suniso® SL68 and ICI Emkarate™ RL68H); comparative tests for R-12 and R-22 with a naphthenic mineral oil (MO, Witco Suniso® 3GS and 4GS); dynamic surface (interfacial) tension reduction; characteristics of the foam formed when the refrigerant leaves the refrigerant-lubricant mixture, following a pressure drop, including foamability and foam stability; found that none of the HFC blends tested favor the foaming process from an interfacial standpoint; concludes that slow absorption rates correspond to a smaller reduction in surface tension, lower foamability, and higher desorption rate; R-134a/POE is an example of a mixture with a fast absorption rate and slow desorption rate, while R-143a/POE exemplifies slow absorption and rapid desorption; paper also concludes that the foamability and foam stability for HFC/POE mixtures are lower than for R-12 or R-22 with mineral oil

S. Gunsel and M. Pozebanchuk (Pennzoil Products Company), **Elastohydrodynamic Lubrication with Polyolester Lubricants and HFC Refrigerants**, report DOE/CE/23810-102 volume I, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, April 1999 (236 pages with 149 figures and 37 tables, available from JMC as RDB9613)

summarizes tests of the elastohydrodynamic (EHD) behavior of lubricants in high-pressure, nonconforming contacts under different conditions of temperature and rolling speed; presents results based on the ultrathin film EHD interferometry technique to predict lubricant effectiveness in the rolling bearing elements, gears, and rotors of compressors; provides data for two naphthenic mineral oils (MO or NMO, Suniso® 3GS and 4GS) with and without R-22, four polyolester lubricants (POE, ICI Emkarate™ RL 32H and 68H, Mobil EAL Arctic® 68, and CPI® Solest® 68) and two polyvinyl ether lubricants (PVE, Idemitsu Kosan FVC 32B and FVC 68B) with and without R-134a, and two POEs (ICI Emkarate™) RL 32H and 68H) and two PVEs (PVE, Idemitsu Kosan FVC 32B and FVC 68B) with and without R-410A at 23, 45, and 65 °C (73, 113, and 149°F); refrigerant concentrations ranged from 0 to 60% by mass; report concludes that all of the lubricants behaved as expected from EHD theory under air and that their comparative rankings by pressure-viscosity coefficients was NMO > PVE > POE; notes that refrigerants have a significant effect on reducing EHD film formation and that film thickness decreases with increasing refrigerant concentration; provides data for modeling the viscosity and pressure-viscosity characteristics of refrigerant-lubricant (RL) mixtures and for determining and optimizing lubricant behavior in EHD contacts of refrigeration compressors; see RDB9614 for measured (raw) data

S. Gunsel and M. Pozebanchuk (Pennzoil Products Company), **Elastohydrodynamic Lubrication with Polyolester Lubricants and HFC Refrigerants - Raw Data**, report DOE/CE/23810-102 volume II, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, April 1999 (222 pages with 9 figures and 65 tables, available from JMC as RDB9614)

presents measured (raw) data for tests of the elastohydrodynamic (EHD) behavior of lubricants in high-pressure, nonconforming contacts under different conditions of temperature and rolling speed; presents results based on the ultrathin film EHD interferometry technique to predict lubricant effectiveness in the rolling bearing elements, gears, and rotors of compressors; provides data for two naphthenic mineral oils (MO or NMO, Suniso® 3GS and 4GS) with and without R-22, four polyolester lubricants (POE, ICI Emkarate™ RL 32H and 68H, Mobil EAL Arctic® 68, and CPI® Solest® 68) and two polyvinyl ether lubricants (PVE, Idemitsu Kosan FVC 32B and FVC 68B) with and without R-134a, and two POEs (ICI Emkarate™) RL 32H and 68H) and two PVEs (PVE, Idemitsu Kosan FVC 32B and FVC 68B) with and without R-410A at 23, 45, and 65 °C (73, 113, and 149°F); refrigerant concentrations ranged from 0 to 60% by mass; report concludes that all of the lubricants behaved as expected from EHD theory under air and that their comparative rankings by pressure-viscosity coefficients was NMO > PVE > POE; notes that refrigerants have a significant effect on reducing EHD film formation and that film thickness decreases with increasing refrigerant concentration; provides data for modeling the viscosity and pressure-viscosity characteristics of refrigerant-lubricant (RL) mixtures and for determining and optimizing lubricant behavior in EHD contacts of refrigeration compressors; see RDB9613 for data analysis and interpretation

B. D. Greig, A. M. Smith, and A. P. Swallow (Castrol International), **Household Compressor Manufacturers Adopting HFC Refrigerants; Compressor Lubricants and Manufacturing Fluids Compatibility,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, October 1993), Alliance for Responsible CFC Policy, Arlington, VA, 100-108, October 1993 (9 pages with 10 tables, RDB3A32)

This paper discusses the compatibility and performance of polyolester (POE) lubricants with R-134a as well as compatibility issues arising from manufacturing residues and moisture. it specifically addresses Castrol Icematic SW, a family of synthetic POE lubricants formulated with a low treat, ashless additive package. The additives improve hydrolytic stability, inhibit copper plating, and reduce compressor component wear. The paper notes that tests, including field trials, have found wear comparable or lower than with R-12 and mineral oil, but that problems remain. One source identified is residual mineral oil lubricants from manufacturing processes, which act as contaminants. These residues contain paraffins that form insoluble flocs when mixed with liquefied R-134a in condensers. The flocs cause system blockage, especially in capillary tubes. The paper cites efforts with equipment manufacturers to identify compatible alternatives, nonchlorinated cleaners, and corrosion preventives. They include an ester wax to replace paraffinic wax as the motor winding lubricant, a multipurpose lubricant that functions as a hydraulic oil for automated post-cleaning assembly equipment, compressor oil for air compressors supplying dried air to the factory, and a component assembly lubricant. The paper notes that POE lubricants were successfully employed for many years in several applications involving high temperatures. New POEs were synthesized for miscibility with R-134a. A table presents the viscosities, pour points, flash points, and critical solution temperatures with R-134a for three viscosity grades. The paper then discusses inhibition of copper plating. A table compares the condition of aluminum, copper, and steel specimens following sealed-tube tests at 175 °C (347 °F) for 14 days for both a nonformulated base stock and fully formulated Icematic SW22 with 50, 250, and 500 ppm of water. The results suggest that plating increases with moisture, but can be partially or fully inhibited with additives depending on the moisture level. The paper notes the need to dry POE lubricants, typically to 50 ppm or even 20 ppm, and that care is required to minimize exposures to atmospheric moisture. The paper then discusses hydrolytic stability, noting that ester base stocks are produced by a reversible reaction of acid(s) and alcohol(s) to yield an ester and water. A table provides total acid number (TAN) data from turbine and oxidation stability tests (TOST) for selected POEs, including a neat base stock. The discussion indicates that the true level of breakdown is likely to be higher, due to losses from the volatility of many of the acid breakdown products. The paper then addresses compressor wear, noting that chlorinated additive compounds and chlorine from refrigerants have historically provided excellent anti-wear properties. Falex pin and vblock wear data are tabulated for naphthenic mineral oil alone and with R-12 as well as for ester base stock and formulated POEs alone, with R-12, and with R-134a. The data suggest that R-134a with the formulated POE results in the lowest wear. A separate table compares compressor efficiency for R-134a with POE in three viscosity grades and for R-134a with an unidentified naphthenic oil. Discussion of the data suggests that the tower viscosities will be preferred for higher compressor efficiency. The paper then reviews chemical cleaners and corrosion preventives used in the manufacture of compressors. Data are provided for Castrol Careclean MP and Rustilo DWX; Rustilo DWX 30 is designed as an ester-based corrosion preventive for compatibility with R-134a and POEs. The paper similarly discusses effects of residual honing oils for compressor component machining and hydraulic oils for assembly. Tabular data show the reduction in lower solution temperature with ester honing and hydraulic oils, such as Castrol CareTech and Hyspin SW32, compared to mineral oils. The paper concludes that system compatibility with R-134a involves consideration of the motor winding wax, corrosion preventives, honing and hydraulic oils, and cleaners in addition to the selection and additives for the POE lubricant.

T. Hamada and N. Nishiura (Mitsubishi Oil Company, Limited, Japan), **Refrigeration Lubricant Based on Polyolester for Use with HFCs and Prospect or Its Application with R-22 (Part 2) Hydrolytic Stability and Compressor Endurance Test Results,** *Proceedings of the 1996 International Refrigeration Conference of Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 279-284, July 1996 (6 pages with 11 figures and 3 tables, RDB6917)

tribological behavior for a pentaerythritol type polyolester (POE) base and formulated oils as a lubricant for use with both R-22 and hydrofluorocarbon- (HFC) refrigerants including R-134a, R-404A and R-407C; hydrolytic and thermal stability; moisture removal effect; reliability tests; compressor endurance tests; roles of additives

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Including epoxy type, antiwear (aryl phosphate and sulfur phosphorous), and others

P. E. Hansen (Danfoss-Flensburg GmbH, Germany), **On the Oil Selection Methodology for New Refrigerants for Small Hermetic Compressors**, paper 3.3, *Proceedings of the International Seminar on New Technology of Alternative Refrigerants - Lubricants and Materials Compatibility* (Tokyo, February 1993), Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 45-50, February 1993 (6 pages with 3 figures and 3 tables, RDB3312)

T. Hayashi, M. Tanaka, K. Takeuchi, K. Takahata, and N. Sakamoto (Mitsui Petrochemical Industries, Limited, Japan), **Carbonate Oils for Unitary Air Conditioners with R-410A,** *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 285-290, July 1996 (6 pages with 5 figures and 7 tables, RDB6918)

R-410A; synthetic carbonate lubricants containing a ß-hindered alkyl and alkylbenzene groups; miscibility with R-410A; thermal stability; lubricity; drop-in test in a rotary, rolling-piston compressor; properties

D. R. Henderson (Spauschus Associates, Incorporated), **Solubility, Viscosity, and Density of Refrigerant/Lubricant Mixtures,** *Proceedings of the 1994 International Refrigeration Conference at Purdue,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 419-424, July 1994 (6 pages with 12 figures and 1 table, RDB4856)

Density is plotted as a function of temperature for R-32 with ISO 100 POE-BA, R-125 with ISO 22 POE-MA and with ISO 32 POE-BA, and R-152a with ISO 68 AB. Daniel Charts are provided for R-32 with ISO 100 POE-BA, R-124 with ISO 68 AB, R-134a with ISO 22 POE-MA, R-143a with ISO 32 POE-BA, and R-152a with ISO 68 AB.

D. R. Henderson (Spauschus Associates, Incorporated), **Solubility, Viscosity, and Density of Refrigerant/Lubricant Mixtures**, report DOE/CE/-23810-34, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, April 1994 (150 pages with 142 figures and 77 tables, available from JMC as RDB4889)

This report presents the findings of a study of the solubility, viscosity, and density of 35 refrigerant-lubricant mixtures. It addresses low (0, 10, 20, and 30% by weight) and high (80, 90, and 100%) refrigerant concentrations. It summarizes results for R-12, R-22, R-32, R-123, R-124, R-125, R-134a, R-142b, R-143a, and R-152a with mineral oil (MO), alkylbenzene (AB), polyalkylene glycol (PAG), and two classes of polyolester (POE) lubricants - pentaerythritol ester branched acid (POE-BA) and pentaerythritol ester mixed acid (POE-MA). Data are provided for the following combinations: R-12 with ISO 32 and 100 MO; R-22 with ISO 32 MO; R-32 with ISO 22 and 68 POE-MA and with ISA 32 and 100 POE-BA; R-123 with ISO 32 and 100 MO and with ISO 32 and 68 AB; R-124 with ISO 32 and 66 AB; R-125 with ISO 22 and 68 POE-MA and with ISO 32 and 100 POE-BA; R-134a with ISO 68 PAG, ISO 22, 68, and 100 POE-BA, and ISO 22, 32, 68, and 100 POE-MA; R-142b with ISO 32 and 78 AB; R-143a with ISO 22 and 68 POE-MA and ISO 32 and 100 POE-BA; and R-152a with ISO 32 and 68 AB and with ISO 22 and 68 POE-MA. Equations and regression coefficients are tabulated for solubility (expressed as vapor pressure), dynamic and kinematic viscosity, and density for each mixture. These results also are shown as plots of density versus temperature and as Daniel Charts, showing kinematic viscosity and solubility versus temperature. The measurements for the low refrigerant concentrations covered 0-100 °C (32-212 °F), except that measurements for R-32, R-125, and R-143a were capped at 75, 65, and 70 °C (167, 149, and 158 °F), respectively, Those for high concentrations covered -40 to 40 °C (-40 to 104 °F), except for R-32, R-123, and R-143a for which the low end of the ranges were changed to -50, -20, and -45 °C (-58, -4, and -49 °F). An appendix explains the experimental technique. It also outlines the theoretical basis for corrections made for vapor space volume in the test apparatus. A second appendix summarizes the lubricant purities, including moisture content, total acid number (TAN), and iron and copper contents. A final appendix identifies the specific lubricants tested, including AB (Shrieve Chemical Zerol® 150 and 300), naphthenic MO (Witco Suniso® 3GS and 5GS), PAG (ICI Emkarox® DGLP 103), POE-BA (Henkel Emery® 2966A, 2968A, 2942A, and 2928A), and POE-MA (Mobil EAL Arctic® 22 and 32; Castrol Icematic® SW32, SW68, and SW100; and ICI Emkarate® RL-375). The report includes an interpretive discussion of the findings by refrigerant.

N. J. Hewitt, J. T. McMullan, P. C. Henderson, and M. G. McNerlin (University of Ulster, UK), **The Effect of Circulating Compressor Lubricant on the Performance of R227ea in Water-to-Water Heat Pumps,** *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 112-120, 1997 (9 pages with 7 figures and 3 tables, RDB9318) examines the use of R-227ea as a refrigerant in high-temperature heat pumps to replace R-114; compares data for R-114, R-134, R-143, R-160, R-227ea, R-236ca, R-236cb, R-236ea, R-236fa, R-254cb, R-C318, R-600 (n-butane), R-600a (isobutane), and R-630; also compares the qualitative suitability in terms of flammability, stability, and toxicity of R-143, R-227ea, R-236ca, R-236cb, R-236ea, R-236fa, R-254cb, and R-C318; examines the performance of R-227ea and the effects of lubricants; summarizes tests of R-227ea with a mixed-acid, polyolester (POE) lubricant (ICI Emkarate™ RL 32S); concludes that R-227ea with the tested POE is satisfactory at higher evaporator superheats and that small amounts (up to 4%) of the oil did not have significant effects, though the drop in evaporator performance can be as high as 10% with 6% circulating lubricant

N. J. Hewitt, J. T. McMullan, B. Mongey, and R. H. Evans (University of Ulster, UK), **From Pure Fluids to Zeotropic and Azeotropic Mixtures: The Effects of Refrigerant-Oil Solubility on Systems Performance**, *International Journal of Energy Research* (IJER), 20(1):57-67, 1996 (11 pages with 11 figures, RDB8514)

discusses effects of circulating compressor lubricants on performance of vapor-compression systems; presents the measured effects on heat transfer of 0, 1.9, 4.7. and 6.4% m/m mineral oil (MO) with R-12; 0, 1, 3, and 5% m/m MO with R-22; a polyolester (POE) lubricant with R-22; 0, 5, and 10% m/m polyolester (POE) with R-134a; and R-407C with a POE; provides a miscibility diagram for R-32, R-125, and R-407C; discusses refrigerant-lubricant (RL) interactions and consequences of refrigerant solubility, and for blends differential solubility of components, in lubricants; concludes that the presence of oils in refrigeration systems is detrimental to system performance by trapping refrigerant in the lubricant in the evaporator; depending on the level of solubility, secondary effects can be seen at low evaporator superheats

N. J. Hewitt and J. T. McMullan (University of Ulster, Northern Ireland, UK), **Refrigerant-Oil Solubility and its Effect on System Performance,** *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:290-296, 1995 (7 pages with 4 figures, RDB7818)

refrigerant-lubricant (RL) effects on system performance: R-12 and R-22 with mineral oil; R-22, R-134a, and R-407C with polyolester (POE); deterioration in evaporator heat transfer; method of predicting the concentration of the circulating lubricant; notes that R-407C is more soluble in the tested POE than R-134a despite is high R-134a content, and suggests that the difference may be due to the presence of R-125

S. Hiodoshi, K. Kawahara, T. Okawa, Y. Fudemato, H. Matsuura, and M. Nomura (Daikin Industries, Limited, Japan), **Evaluation of Refrigerant Oil and Sliding Materials for Alternative Refrigerant**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 46-55, November 1997 (10 pages with 11 figures and 4 tables, RDB8326)

discusses lubricant selection with focus on a polyolester (POE) and polyvinyl ether (PVE) for use with R-22, R-407C, and R-410A; summarizes materials selections for key wear components in a scroll compressor including the journal bearing and Oldham ring; provides comparative data for lubricants and discusses shortcomings in conventional durability tests

D. F. Huttenlocher (Spauschus Associates, Incorporated), **Chemical and Thermal Stability of Refrigerant-Lubricant Mixtures with Metals**, report DOE/CE/23810-5, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 9 October 1992 (126 pages with 75 figures and 27 tables, available from JMC as RDB3608; several of the figures, specifically the IR spectra, are difficult to read)

This report presents stability data, based on sealed tube tests, for 21 mixtures of refrigerants and lubricants in the presence of a valve steel strip, as catalyst. Tables present results for R-11 with mineral oil (MO) and with a white naphthenic MO; R-22 with MO; R-32 with pentaerythritol ester mixed acid and with polypropylene glycol (PPG) butyl monoether; R-123 with MO and with white naphthenic MO; R-124 with alkylbenzene (AB); R-125 with PPG butyl monoether, modified polyglycol, and pentaerythritol ester mixed acid; R-134 with pentaerythritol ester mixed acid; R-134a with PPG butyl monoether, PPG diol, modified polyglycol, three pentaerythritol esters (two of them mixed acids); R-142b with alkylbenzene; R-143a with pentaerythritol ester mixed acid; and R-152a with AB. Each test mixture was aged at three temperature levels, generally 150, 175, and 200 °C (221, 302, and 347 °F); tests were performed at other temperatures when warranted. The information provided includes the specific materials and aging conditions for each combination tested, visual observations on the aged sealed tubes, and results of chemical analyses. The last includes gas chromatograms of the vapor-phase contents as well as chloride and fluoride ion contents for mixtures containing hydrochlo-

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rofluorocarbons (HCFCs) hydrofluorocarbon (HFCs), respectively. Total acid number (TAN) values and infrared analyses (IR) are presented; size exclusion chromatography (SEC) is summarized for mixtures including polyalkylene glycol (PAG) lubricants. The findings indicate that the HFCs tested and R-22 are very stable and do not undergo measurable chemical reactions or thermal decomposition, even in the presence of lubricants, for the conditions tested. R-124 and R-142b have stability properties intermediate between the HFCs and R-12. R-123 is more reactive, but offers stability improvement by a factor of ten over R-11. All of the pentaerythritol ester and PAG fluids showed changes in chemical structure after exposures at 200 °C (347 °F), and in some cases at 150 °C (302 °F) and 175 °C (347 °F). An appendix summarizes the test results, including tabulated findings and gas chromatograms. A second presents IR spectra and SECs of the lubricants before and after aging. A third appendix recaps the refrigerants and lubricants tested as well as purity measurements taken. Gas chromatograms are provided for each of the refrigerants. Acidity, water content, and metal content are tabulated for each of the lubricants. The MOs tested were Witco Suniso® 3GS (ISO VG32) and Freezene Naphthenic Heavy white oil (ISO VG46). The AB was Shrieve Zerol® 150. The PAGs included ICI Emkarox® PPG butyl monoether (ISO VG32) and Dow Chemical P245 PPG diol (ISO VG22). The pentaerythritol esters (PEs) included Castrol Icematic® SW32 branched acid (ISO VG32), ICI Emkarate™ RL mixed acids (ISO VG22), and Henkel Emery® 4078X (2928 ISO VG 100) 100 cSt.

S. T. Jolley, K. E. Davis, and G. R. Malone, **The Effect of Desiccants in HFC Refrigeration Systems Using Ester Lubricants,** Lubrizol Corporation, Wickliffe, OH, 1996 (12 pages with 8 figures, available from JMC as RDB6903)

investigation of moisture impacts with use of polyolester (POE) lubricants; potential for acid contamination of systems using hydrofluorocarbon (HFC) refrigerants and POEs from the lubricant and additive hydrolysis; water potential and role of desiccants in refrigeration systems; bench and accelerated compressor testing shows that hydrolysis increases, as evidenced by a decrease in water and increase in total acid number (TAN); role of the carboxylic acid from POE hydrolysis over a 5000 hr test; experiments show that moisture can be transferred from desiccants to lubricants and that the water content of lubricants reaches an equilibrium with other parts of the system; capillary tube blockage tests with wet and dry systems, each with and without a desiccant show low blockage in dry systems, but a quick increase when doped with carboxylic acid; the paper concludes that moderate water contamination of refrigeration systems may be less of a long-term problem than perceived; it further concludes that while POEs can undergo hydrolysis with sufficient water, the combination of desiccant use and affinity of refrigerants to associate with water reduce its contact with the lubricant; finally, that use of POEs prepared with α-branched acids and use of hydrolysis inhibiting additives further reduce the potential for lubricant degradation

S. Komatsuzaki, Y. Homma, Y. Itoh, K. Kawashima, and T. Iizuka (Hitachi Limited, Japan), **Polyol Esters as HFC-134a Compressor Lubricants,** *Lubrication Engineering,* 50(10):801-807, 1994 (7 pages, rdb6370)

R-1342, polyolester (POE) lubricants

S. Komatsuzaki and T. Iizuka (Hitachi Limited, Japan), **Miscibility and Lubricity of Polyol Ester-Based Refrigerator Lubricants**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC), Alliance for Responsible CFC Policy, Arlington, VA, 92-99, October 1993 (8 pages with 9 figures and 1 table, available from JMC as RDB3A31)

This paper provides data on the miscibility and lubricity of mixtures of R-134a with polyolester (POE) lubricants, including neopentyl glycol (NPG), pentaerythritol (PE), and trimethylol propane (TMP) esters. It briefly reviews the rationale for transition, to hydrofluorocarbon refrigerants and the accompanying introduction of new lubricants and other materials. It cites the dependence on hydrogen bonding between the refrigerant and lubricant for miscibility, and discusses the influence of the lubricant's molecular structure on miscibility. The paper reviews the manufacture of esters from reactions of alcohols with fatty acids. Figures show the miscibility of R-134a with TMP and PE esters as well as with fatty acids as functions of temperature and lubricant fraction for straight- and branched-chain acids. The paper then discusses and shows plots of the upper critical solution temperature (UCST) dependence on the number of carbon atoms in the acids for NPG, PE, and TMP esters. The paper discusses the anticipated use of R-32 in blends and tabulates the viscosity of eight POEs and their UCSTs with R-32 and R-134a. It discusses lubricity tests and notes that measured results were entirely different in refrigerant and air environments. It describes lubricity tests with refrigerant lubricant mixtures and gives plots for R-12 with alkylbenzene and for R-134a with an unidentified, additized, TMP ester. A final plot shows the seizure load dependance of these mixtures on the refrigerant-lubricant ratio. The paper concludes that better miscibility can be achieved with branched acids and that higher lubricity is needed with R-134a than with R-12, since the refrigerant offers no lubricity itself. Further, the use of extreme pressure (EP) additives allows R-134a/POE mixtures to match the lubricity of R-12 with mineral oils or alkylbenzenes. The paper notes, however, that the lubricity of R-134a/POE drops sharply when the refrigerant exceeds 50% of the mixture by volume.

M. A. Krevalis, C. B. Duncan, and G. W. Davis, **The Effect of Structure on the Performance of Polyol Esters as Synthetic Lubricants**, 49th Annual Meeting, Pittsburgh, PA, May 1994), Society of Tribologists and Lubrication Engineers (STLE), 1994 (rdb5125)

polyolester, POE

K. C. Lilje, M. Sabahi (Albermarle Corporation), and S. Hamid (Hüls America Incorporated), **Polybasic Esters: Novel Synthetic Lubricants Designed for Use in HFC Compressors,** paper SD-95-8-2, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):935-939, 1995 (5 pages with 1 figure and 12 tables, RDB6369)

polybasic ester (PBE) lubricants resulting from reactions of acrylate esters with malonate-esters (malonate-acrylate Michael adducts)

K. C. Lilje and M. Sabahi (Albermarle Corporation), **A Novel Class of Synthetic Lubricants Designed for HFC Compressors,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 24-26 October 1994), Alliance for Responsible Atmospheric Policy, Arlington, VA, 145-153, October 1994 (9 pages with 2 figures and 8 tables, RDB6914)

polybasic ester (PBE) lubricants resulting from reactions of acrylate esters with malonate-esters; physical properties, role of additives, chemical and hydrolytic stability, Falex wear tests, hygroscopicity, compressor testing

W. L. Martz (Ford Motor Company), C. M. Burton, and A. M. Jacobi (University of Illinois at Urbana-Champaign), **Vapor-Liquid Equilibria for R-22, R-134a, R-125, and R-32/125 with a Polyol Ester Lubricant: Measurements and Departure from Ideality**, *Transactions* (Winter Meeting, Atlanta, GA, 17-21 February 1996), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 102(1):367-374, 1996 (8 pages with 10 figures and 1 table, RDB7A25)

presents the effects of a polyolester (POE) lubricant on equilibrium pressure, liquid density, and viscosity for R-22, R-125, and R-134a at varying temperatures and concentrations; also presents preliminary vapor-liquid equilibrium (VLE) data and miscibility observations for R-410A with the ISO 68 POE; summarizes modeling of real-gas behavior using the vapor-phase fugacity and accounting for the vapor pressure effects on liquid fugacities with the Poynting effect; positive, negative, and mixed deviations from the Lewis-Randall rule are observed in the activity coefficient behavior; departures from ideal behavior are related to molecular size differences, intermolecular forces in the mixture, and other factors

W. L. Martz (Ford Motor Company), C. M. Burton (University of Illinois at Urbana-Champaign), and A. M. Jacobi (Ford), **Local Composition Modeling of the Thermodynamic Properties of Refrigerant and Oil Mixtures**, *International Journal of Refrigeration* (IJR), 19(1):25-33, January 1996 (9 pages with 5 figures and 2 tables, RDB7A26)

describes six local composition models for the thermodynamic behavior of refrigerant-lubricant mixtures; compares the predictive abilities of the models for R-12, R-22, R-125, and R-134a with various oils to published data; concludes that the Wilson (an extension of Flory-Huggins theory) and Heil (semi-empirical) equations provide the most consistent results, with the Heil equation providing a modest improvement over the Wilson model; other models addressed include nonrandom, two-liquid theory (NTRL), Tsuboka and Katayama, Wang and Chao, and universal, quasi-chemical theory (UNIQUAC)

T. Matsuzaki and M. Akei (Calsonic Corporation), **The Friction and Wear Behavior in Refrigerant Atmosphere**, paper 2.2, *Proceedings of the International Seminar on New Technology of Alternative Refrigerants - Lubricants and Materials Compatibility* (Tokyo, February 1993), Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 27-32, February 1993 (6 pages with 13 figures, RDB3310)

S. Macaudiere, A. Giraud, P. Weiss (Elf Atochem S.A., France) and P. Sanvi (Elf Centre de Recherche de Solaize, France), **Experimental Assessment of Oil Return with CFC and HCFC Alternatives**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 115-123, November 1997 (9 pages with 7 figures and 2 tables, RDB8334)

discusses factors that influence lubricant selections including refrigerant-lubricant miscibility,

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refrigerant solubility in the oil, and fluidity; presents a test device to measure oil-return; plots miscibility for R-12, R-134a, R-409A, and two unidentified blends with a naphthenic mineral oil (Witco Suniso® 3GS); plots and tabulates solubility and plots oil-return rates for the same combinations; compares miscibility for R-22 and R-407C with a mineral oil, alkylbenzene (AB), polyolester (POE), and polyvinyl ether (PVE) lubricants; concludes that oil return is more related to miscibility at low temperature than at medium or high temperatures

H. H. Michels and T. H. Sienel (United Technologies Research Center, UTRC), **Viscosity Modeling of Refrigerant/Lubricant Mixtures**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 96-105, November 1997 (10 pages with 3 figures and 1 table, RDB8332)

presents a two-parameter model to predict the liquid viscosity of refrigerant-lubricant mixtures: model is described as similar to the Wohl [n]-suffix expansion for nonideal liquid mixtures; model is compared to the Arrhenius, Frenkel, Grunberg-Nissan, Kendall, McAllister (3- and 4-body), and Yokozeki models; paper presents plots of the viscosity as a functions of the refrigerant mass fractions for R-22 with an alkylbenzene (AB), R-134a with a polyolester (POE), and R-410A with a polyvinyl ether (PVE); these plots show the comparative abilities of the identified models to represent the full range, including refrigerant-rich and lubricant-rich mixtures; concludes that the new model is adequate for most engineering applications, but notes that further studies with multicomponent mixtures and other refrigerant-lubricant combinations are underway

H. H. Michels and T. H. Sienel (United Technologies Research Center, UTRC), **Solubility Modeling of Refrigerant/Lubricant Mixtures**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 49-58, October 1995; republished as report DOE/CE/23810-65B, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 1995 (10 pages with 6 figures, available from JMC as RDB5A45)

general model (NISC) for predicting the solubility properties of refrigerant-lubricant mixtures, Wohl model, excess Gibb's energy of nonideal solutions, R-407C, R-410A, polyolester lubricant

J. Mitrovic (Technische Universität Berlin, Germany), **Verdampfung von strömenden Kältemittel-Öl-Gemischen im Bereich der Mischungslücke** [Flow Evaporation of Refrigerant-Oil Mixtures in the Immiscible Region], *Ki Klima-Kälte-Heizung*, Germany, 19(3):348-351, September 1991 (4 pages in German, rdb9421)

flow boiling heat transfer of refrigerant-lubricant (RL) mixtures

K. Mizuhara, M. Akei, and T. Matsuzaki, **The Friction and Wear Behavior in a Controlled Alternative Refrigerant Atmosphere,** *Tribology Transactions* (ASME/STLE Tribology Conference, San Diego, CA, 18-21 October 1992), paper 92-TC-3B-3, Society of Tribologists and Lubrication Engineers (STLE), 37(1):120-128, 1994 (9 pages, rdb4C26)

lubricant performance

K. Mizui, M. Tanaka, T. Hayashi, K. Takahata, and N. Sakamoto (Mitsui Petrochemical Industries, Limited, Japan), **New Lube Oil for Unitary Air Conditioner**, paper 5.4, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 119-123, December 1994 (5 pages with 2 figures and 9 tables; in Japanese with abstract, figures, and tables in English; RDB5422)

R-407C; carbonate, ester, acid ether synthetic lubricants; hindered and nonhindered carbonates; lubricity, viscosity, miscibility, stability with metals

M. Muraki, K. Takagawa (Mitsubishi Oil Company, Limited, Japan), and D. Dong (Sanseki Techno Company, Limited, Japan), **Refrigeration Lubricant Based on Polyolester for Use with HFCs and Prospect or Its Application with R-22 (Part 1) Tribological Considerations**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 273-278, July 1996 (6 pages with 10 figures and 3 tables, RDB6916)

tribological behavior for a pentaerythritol type polyolester (POE) base and formulated oils and an alkylbenzene having a branched alkyl substituent with R-22, R-134a, R-404A, and R-407C; effects of refrigerants and additives; surface observations and analysis

M. Muraki (Mitsubishi Oil Company, Limited, Japan), **Refrigeration Lubricants Based on Polyolester for Alternative Refrigerants,** paper 5.1, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment*

(Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 101-106, December 1994 (6 pages with 16 figures, in Japanese with abstract and figures in English, RDB5419)

miscibility, hydrolytic stability, tribology, wear, rotary rolling-piston compressor, R-134a, R-32/125/134a

M. Nomura, K. Sakitani, S. Hiodoshi, M. Minowa, and T. Kato (Daikin Industries, Limited, Japan), **Evaluation of Oil Applicable to HFC-134a**, *Proceedings of the 1994 International Refrigeration Conference at Purdue,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 135-140, July 1994 (6 pages with 2 figures and 2 tables, RDB4817)

R-134a, polyolester

P. O'Neill and T. E. Rajewski (CPI Engineering Services, Incorporated), **Lubricants for Use in Ammonia Systems**, *Proceedings of the Conference on Ammonia Refrigeration Today,* London, UK, 1994 (rdb9249)

refrigeration lubricants for R-717 (ammonia)

M. B. Pate, S. C. Zoz, and L. J. Berkenbosch (Iowa State University of Science and Technology), **Miscibility of Lubricants with Refrigerants**, report DOE/CE/23810-18, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, July 1993 (262 pages with 73 figure and 151 tables, available from JMC as RDB4502)

This report provides detailed miscibility data for 10 alternative refrigerants with 14 lubricants, based on experiments conducted in two phases. The first involved screening using refrigerant concentrations of 10, 50, and 95%. The second entailed further measurements at 20, 35, 65, 80, and 90%. The report presents the methods, apparatus based on test cells in temperature-controlled baths, and significant results. Ten tables summarize the miscibility data for each refrigerant by nominal concentration in each of 14 lubricants. 72 plots show the miscible and immiscible regions by mass fraction (0.0 to 1.0) and temperature (-50 to 60 °C, -58 to 140 °F); plots are omitted for combinations exhibiting full miscibility. The refrigerants are R-22, R-32, R-123, R-124, R-125, R-134, R-134a, R-142b, R-143a, and R-152a. The lubricants include two naphthenic mineral oils (Witco Suniso® 3GS and 4GS) and two alkylbenzenes (Shrieve Zerol® 150 and 300). They also included five polyalkylene glycol (PAG) samples: two polypropylene glycol butyl monoethers (ICI Emkarox® VG32 and VG58), two polypropylene glycol diols (Dow Chemical P425 and P1200), and a modified polyglycol (AlliedSignal BRL-150). Five polyolesters (POE) were tested, all pentaerythritol esters: three mixed acids (ICI Emkarate™ RL 22H, formerly identified as RL 244, and Castrol Icematic® SW32 and SW100) and two branched acids (Henkel Emery® E2927 and E2928). Each of the refrigerants tested is miscible with at least one of the lubricants, with the exception of R-143a, which exhibits partial miscibility with each of the lubricants. The moisture, iron, and copper contents as well as acid numbers are tabulated for the test lubricants. An appendix comprising 140 tables provides a summary of qualitative observations (two phase, clear, slightly hazy, or hazy) by nominal temperature and concentration as well as the precise measurements of the mass fractions and actual temperatures.

T. Pyziak and D. W. Brinkman, **Recycling and Re-Refining Used Lubricating Oils,** *Lubrication Engineering,* 49(5):339 ff, 1993 (rdb6382)

lubricant recovery, disposal and reuse of oils

S. J. Randles and M. G. Penman (ICI Chemicals and Polymers Limited, UK), **Handling and Disposal of Polyol Ester Refrigeration Lubricants**, paper SD-95-8-4, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):947-957, 1995 (11 pages with 8 figures and 4 tables, RDB-6375)

polyolester (POE) lubricants, storage, handling, safety, additives, disposal and reuse of oils

J. L. Reyes-Gavilán, G. T. Flak, T. R. Tritcak (Witco Corporation), and C. B. Barbour (Americold/White Consolidated Industries), **Enhanced Naphthenic Refrigeration Oils for Household Refrigerator Systems,** paper 4019, *Transactions* (Winter Meeting, Philadelphia, PA, 26-29 January 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 103(1):95-106, 1997 (12 pages with 7 figures and 10 tables, RDB7C11)

summary of bench test evaluations of enhanced naphthenic mineral oil (MO) lubricants for hydrofluorocarbon (HFC) refrigerants; comparisons to polyolester (POE) lubricants; compatibility; stability; lubrication performance; wear; viscosity; heat transfer; properties; retrofit

J. L. Reyes-Gavilán, G. T. Flak, and T. R. Tritcak (Witco Corporation), **Lubricants for Refrigeration Compressor Applications,** unpublished paper presented at the International CFC and Halon Alternatives Conference (Washington, DC), October 1993 (13 pages with 4 figures and 3 tables, available from JMC as RDB3A55)

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This paper presents an experimental study to evaluate oil return in domestic refrigerator-freezers using R-134a. A refrigerant immiscible, naphthenic mineral oil (MO, Witco Suniso® 1GS) was tested in a 0.6 m^3 (20 cf) side-by-side refrigerator and in a 0.4 m^3 (14.6 cf) top-mount unit for 22 months. The aim was to demonstrate suitability of the lubricant and that proper oil return results. The same lubricant type was compared to a fully miscible polyolester (POE, Suniso® 1GS SL-10) in a test stand, designed with a difficult oil-return configuration. Tabular data are presented to compare the cabinet and freezer temperatures for drop-in evaluation of the mineral oil with R-12 and R-134a and to compare the typical properties of the mineral oil and POE. A third table summarizes the test conditions for the oil-return test stand. Plots show the gas solubility and viscosity curves for each lubricant in R-134a at -23 and 0 °C (-10 and 32 °F). The experimental procedures and findings are discussed. The paper concludes that oil return to the compressor is very similar for both lubricants at typical suction conditions similar for domestic refrigerators. Refrigerant gas velocity is noted as playing an important role in lubricant return for poor oil return configurations. The results also show that differences in cabinet and freezer temperatures, between the two refrigerant/lubricant systems, are not due to oil trapping in the heat exchangers.

J. L. Reyes-Gavilán (Witco Corporation), **Lubricants for Refrigeration Compressor Applications,** seminar presentation charts (Annual Meeting of the American Society. of Heating, Refrigerating, and Air-Conditioning Engineers, ASHRAE, Denver), Witco Corporation, Oakland, NJ, June 1993 (19 pages with 3 figures and 9 tables, available from JMC as RDB3A01)

These charts summarize an unpublished presentation on possible lubricant choices for use with hydrochlorofluorocarbon (HFC) refrigerants. The provide bench test and performance evaluation findings on polyolester (POE), dibasic acid ester, and naphthenic mineral oil (MO) lubricants. Two charts summarize typical properties of seven POEs (Witco Suniso® SL10, SL15, SL22, SL32, SL46, SL68, and SL100) and three dibasic acid esters (Witco R-72-0A, R-72-0B, and R-84-0). Stability test results in the presence of R-134a, steel, copper, and aluminum at 175 °C (347 °F) for up to 56 days and Falex wear evaluations are presented for four base and four additized POEs and the three dibasic acid esters. Hydrolytic stability test findings also are tabulated. A table summarizes miscibility ranges for four of the POEs with R-125, R-134a, R-404A, R-125/143a (45/55), R-32/125 (60/40), and R-32/125/134a (formulation unspecified). Viscosity and solubility with R-134a are plotted for SL10 and SL32 at 125 °C (257 °F) and for a mineral oil (Witco Suniso® 1GS) at 0 °C (32 °F).

J. L. Reyes-Gavilán (Witco Corporation), **Performance Evaluation of Naphthenic and Synthetic Oils in Reciprocating Compressors Employing R-134a as the Refrigerant,** paper 3656, *Transactions* (Winter Meeting, Chicago, IL, 23-27 January 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(1):349-360, 1993 (12 pages with 12 figures and 6 tables, limited copies available from JMC as RDB4C35)

lubricating ability and materials compatibility of naphthenic mineral oil (MO), alkylbenzene, polyalkylene glycol (PAG), and polyolester (POE) lubricants; wear, copper plating, discoloration

K. S. Sanvordenker (Tecumseh Products Company), **Durability of HFC 134a Compressors - the Role of the Lubricant,** *Proceedings of the 42nd Annual International Appliance Technical Conference* (University of Wisconsin, Madison, WI, May 1991), IATC, Batavia, IL, 37-50, 1991; reprint by Tecumseh Products Company, Tecumseh, MI, 1991 (8 pages with 2 figures and 2 tables, RDB2216)

Properties of polyalkylene glycol (PAG) and polyolester lubricants are examined, with emphasis on inherent thermal stability and suitability for use with R-134a in refrigeration compressors. The PAGs addressed include diols, monoethers, ester-ethers, and diethers, all stabilized with 200 ppm BHT. Plots of hygroscopicity and miscibility of PAGs with mineral oils are provided. The decomposition kinetics, based on sealed-tube tests, are tabulated. The effects summarized include temperature (177-260 °C, 350-500 °F), presence of metals (steel, copper, and aluminum) or R-134a, and PAG type. Problems of hygroscopicity, incomplete miscibility with mineral oils, and incompatibility with chlorinated solvents exist, but they can be handled by proper housekeeping procedures. Lack of thermal stability, even in the absence of metals, at 177-204 °C (350-400 °F) is identified as a key shortcoming for the PAG candidates. The effects of time, metal catalysts, and initial moisture are tabulated for polyolesters, again at elevated temperatures (204-260 °C, 400-500 °F). Pentaerythritol tetraester is emphasized due, in part, to its better miscibility with R-134a compared to other neopentyl esters. Decomposition also was observed, but only in the presence of steel. A metal passivator specific to steel was found to provide a simple remedy.

G. D. Short, T. E. Rajewski, and J. E. Oberle (CPI Engineering Services, Incorporated), **Refrigeration**

Lubricants - Current Practice and Future Development, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 265-271, July 1996 (7 pages with 6 figures and 1 table, RDB6912)

overview of synthetic lubricants including alkylbenzene (AB), carbonates, fluorosilicones, mineral oil, perfluoroethers, polyalphaolefin (PAO), polyalkylene glycol (PAG), polyolester (POE), PAG-ester blends, and other esters; table showing use of these lubricants for R-22, R-23, R-123, and R-134a; miscibility, solubility, viscosity, stability, system cleanliness, and wear and compressor durability tests with hydrofluorocarbon (HFC) refrigerants; reviews options for R-717 (ammonia) and hydrocarbons; miscibility of difunctional PAGs of differing average molecular weight (AMU) with R-134a; miscibility changes of POEs from different starting alcohols (dipentaerythritol, pentaerythritol, and trimethylol propane bases); comparative miscibility of three experimental lubricants with R-23, R-134a, R-404A, and R-410A; Daniel Plots with R-134a and R-404A; relative dilution of three POE lubricants with R-404A

G. D. Short and T. E. Rajewski (CPI Engineering Services, Incorporated), **Practical Aspects for Using Soluble Synthetic Lubricants for Ammonia Refrigeration Applications**, *Proceedings of the 1996 Frigaire Conference,* Johannesburg, South Africa, 1996 (rdb9251)

refrigeration lubricants for R-717 (ammonia)

G. D. Short (CPI Engineering Services, Incorporated) and R. C. Cavestri (Imagination Resources, Incorporated, IRI), **High-Viscosity Ester Lubricants for Alternative Refrigerants,** paper AN-92-5-2, *Transactions* (Winter Meeting, Anaheim, CA, January 1992), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 98(1):789-795, 1992 (7 pages with 3 figures and 5 tables, RDB2102)

This paper describes the development of high-viscosity (ISO 68 and above), modified polyolester lubricants and their interactions with refrigerants. Typical properties are presented for 11 conventional and modified pentaerythritol (PE) esters, including several di- and tri-PEs, as well as for a modified trimethylolpropane (TMP) ester. Data are reported with R-123, R-134a, R-152a, R-E134, and R-E245. The apparatus used to measure viscosity and density is described. The viscosity of a modified, high-viscosity ester with R-134a is presented for evaluation of the hydrodynamic lubrication and sealing of compression areas. Chemical and thermal stability and lubricity test results are provided for durability considerations.

R. L. Shubkin, **Polyalphaolefins**, *Synthetic Lubricants and High Performance Functional Fluids,* Marcel Dekker, Incorporated, New York, NY, 1993 (rdb4646)

PAO lubricants; review of polyolester (POE) lubricants made by combining neopentyl alcohols with organic acids; alcohols include neopentyl glycol (NPG), trimethylol propane (TMP), pentaerythritol (PE), and dipentaerythritol (Di-PE) types

H. W. Sibley (Carrier Corporation), **Oil Foaming Characteristics - The Forgotten Design Parameter with HFC-134a,** paper 5.4, *Proceedings of the International Seminar on New Technology of Alternative Refrigerants - Lubricants and Materials Compatibility* (Tokyo, February 1993), Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 101-104, February 1993 (4 pages with 5 figures, RDB3319)

This paper addresses differences in interactions between R-134a with synthetic lubricants and chlorofluorocarbons (CFCs) with mineral oils. The discussion notes the importance of refrigerant-lubricant solubility for oil return to the compressor. The consequent role of the refrigerant as a lubricant contaminant, and specifically reduction in viscosity and hydrodynamic lubrication, is examined. The effect of rapid refrigerant vapor release, called foaming, is explained. A plot compares the vapor pressure of R-134a in a polyolester (POE) to R-12 in a mineral oil (MO) at 27 and 79 °C (80 and 174 °F) with 10-70% refrigerant. The nature of the resultant foams are characterized, that for R-12/MO as a stable froth and that of R-134a/POE as an unstable or quick breaking foam. Comparative foam heights are plotted and contrasted for oil-rich conditions, as in compressor crankcases, and oil-lean conditions, as in evaporators of centrifugal chillers. Significant differences are noted for the former. Desorption dynamics of the two refrigerant-lubricant pairs are discussed and plotted under driving temperature differences of 37 and 171 °C (67 and 308 °F). R-134a is shown to desorb more rapidly at common thermal gradients. The paper concludes that vapor-venting needs to be altered in R-134a compressors. While the change can be readily dealt with in new designs, the difference in venting must be considered in equipment conversions. The paper notes a need to examine effects of different foaming characteristics on heat transfer.

L. I. Sjöholm (Teknikgruppen AB) and G. D. Short (CPI Engineering Services, Incorporated), **Twin-**

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Screw Compressor Performance and Complex Ester Lubricants with HCFC-22, *Proceedings of the 1990 International Compressor Engineering Conference at Purdue*, edited by W. Soedel, Purdue University, West Lafayette, IN, 724-732, July 1990 (9 pages with 8 figures, RDB2222)

L. I. Sjöholm (Teknikgruppen AB) and G. D. Short (CPI Engineering Services, Incorporated), **Twin-Screw Compressor Performance and Suitable Lubricants with HFC-134a**, *Proceedings of the 1990 International Compressor Engineering Conference at Purdue*, edited by W. Soedel, Purdue University, West Lafayette, IN, 733-740, July 1990 (8 pages with 7 figures (8 pages, RDB2223)

H. O. Spauschus and D. R. Henderson (Spauschus Associates, Incorporated), **New Working Fluids for Refrigeration**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:1006-1012, 1995 (7 pages with 1 figure and 4 tables, rdb7937)

development of viscosity, solubility (vapor pressure), and density - expressed as mathematical models, density plots, and Daniel Charts - for 35 refrigerant-lubricant pairs; working-fluid viscosities for nine representative combinations of R-12, R-134a, and R-152a with alkylbenzene (AB), mineral oil (MO), and polyolester (POE) lubricants

H. O. Spauschus, D. R. Henderson, and H. D. Grasshoff (Spauschus Associates, Incorporated), **Lubricants for Hydrocarbon Refrigerants**, *New Applications of Natural Working Fluids in Refrigeration and Air Conditioning* (proceedings of the meeting of IIR Commission B2, Hannover , Germany, 10-13 May 1994), International Institute of Refrigeration (IIR), Paris, France, 153-160, 1994 (8 pages, RDB6C24)

lubricants, properties of refrigerant-lubricant mixtures

H. O. Spauschus, D. R. Henderson, and D. F. Huttenlocher (Spauschus Associates, Incorporated), **Boundary Lubrication Properties of Alternative Working Fluids**, paper 3.1, *Proceedings of the International Seminar on New Technology of Alternative Refrigerants - Lubricants and Materials Compatibility* (Tokyo, February 1993), Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 33-38, February 1993 (6 pages with 7 figures and 2 tables, RDB3311)

lubricants, properties of refrigerant-lubricant mixtures

H. O. Spauschus, D. R. Henderson, and R. Rohatghi (Spauschus Associates, Incorporated), **SAE Cooperative Research Program: HFC-134a Lubricant Study, Final Report,** Society of Automotive Engineers (SAE), Warrendale, PA, 6 November 1992 (130 pages with 105 figures and 49 tables, RDB3107)

R-134a

N. Stosic, L. J. Milutinovic, K. Hanjalic, and A. Kovacevi, **Investigation of the Influence of Oil Injection upon the Screw Compressor Working Process**, *International Journal of Refrigeration* (IJR), 15(4):206-220, May 1992 (15 pages, rdb4C38)

M. Sunami, M. Saito, K. Takigawa, S. Suda, and U. Sasaki (Nippon Oil Company Limited, Japan), **Lubricity of AB and AB Derivates in Compressor Durability Tests**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 303-308, July 1996 (6 pages with 4 figures and 12 table, RDB6921)

evaluation of the antiwear properties of alkylbenzene (AB) lubricants with a phosphate additive in rotary, rolling-piston compressors; solubility R-134a with AB and mineral oil; kinematic viscosity of AB with R-601 (n-pentane), added for oil return for immiscible AB lubricants

M. Sunami, K. Takigawa, S. Suda, and U. Sasaki (Nippon Oil Company Limited, Japan), **New Immiscible Refrigeration Lubricant for HFCs**, paper SD-95-8-3, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):940-946, 1995 (7 pages with 4 figures and 8 tables, RDB6374)

low viscosity alkylbenzene (AB) lubricants, solubility with refrigerants, oil return, miscibility at high temperatures, effects of impurities, chemical stability, lubricity

M. Sunami (Nippon Oil Company, Limited, Japan), **New Immiscible Refrigeration Lubricant for HFCs,** paper 5.5, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 124-129, December 1994 (6 pages with 2 figures and 8 tables; in Japanese with abstract, figures, and tables in English; RDB5423)

R-134a, R-407C, alkylbenzene (AB) in rotary, rolling-piston compressors

M. Sunami, K. Takigawa, and S. Suda (Nippon Oil Company, Limited, Japan), **New Immiscible Refrigeration Lubricant for HFCs**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 129-134, July 1994 (6 pages with 6 figures and 9 tables, RDB4816)

alkylbenzene (AB) in rotary, rolling-piston compressors

M. Sunami, K. Takigawa, and S. Suda (Nippon Oil Company, Limited, Japan), **Optimization of POE Type Refrigeration Lubricants**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 153-158, July 1994 (6 pages with 6 figures and 9 tables, RDB4820)

S. G. Sundaresan (Copeland Corporation), **Compressor Tribology and Other System Requirements for POE Lubricants with HFC Refrigerants**, paper 6.5, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 156-161, December 1994 (6 pages with 5 tables, available from JMC as RDB5429)

tribology, polyolester lubricants, oil return, heat transfer

A. Swallow, A. Smith, and B. Greig (Castrol International, UK), **Control of Refrigerant Vapor Release from Polyol Ester/Halocarbon Working Fluids**, paper SD-95-8-1, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):929-934, 1995 (6 pages with 6 figures and 4 table, RDB6368)

polyolester (POE) lubricants, outgassing of refrigerants, lubrication failure due to vapor lock of the oil pump or degreasing of contact surfaces

M. Takagi (Idemitsu Kosan Company, Limited, Japan), **New Non-Ester Type Lubricants for Alternative Refrigerants**, paper 5.3, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 113-118, December 1994 (6 pages with 6 figures and 3 tables; in Japanese with abstract, figures, and tables in English; RDB5421)

R-22 with mineral oil, R-134a with new non-ester synthetic lubricant, lubricity, contamination, stability with metals

H. Takahashi and T. Kaimai (Japan Energy Corporation, Japan), **New Type Lubricant for Ammonia Refrigerating Systems**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 309-314, July 1996 (6 pages with 5 tables, RDB6922)

R-717, miscible polyalkylene glycol (PAG) lubricant; stability; lubricity; comparisons to alkylbenzene (AB), naphthenic mineral oil, and polyolester (POE) lubricants; properties

K. Takahata, M. Tanaka, T. Hayashi, K. Mizui, and N. Sukamoto (Mitsui Petrochemical Industries, Limited, Japan), **New Lube Oil for Stationary Air Conditioner**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 141-146, July 1994 (6 pages with 4 figures and 7 tables, RDB4818)

carbonate lubricants, R-407C

Y. Takaishi and K. Oguchi (Kanagawa Institute of Technology, Japan), **Solubility of R-32 and Polyolester Lubricant Mixtures**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:568-574, 1995 (7 pages with 5 figures and 2 tables, rdb7903)

measurements of the solubilities for mixtures of R-32 and a Kyodo Oil polyolester lubricant; apparatus is described and shown schematically; concludes that R-32 and POE are partially miscible

Y. Takaishi, M. Izumi, and K. Oguchi (Kanagawa Institute of Technology, Japan), **Measurements of the Solubility for the System of HFC-125 and Polyol Ester Lubricant,** *CFCs, the Day After* (proceedings of the IIR meeting, Padova, Italy, 1994), International Institute of Refrigeration (IIR), Paris, France, 99-105, September 1994 (7 pages, RDB5B26)

R-125, polyolester (POE) lubricant, properties

Y. Takaishi and K. Oguchi (Kanagawa Institute of Technology, Japan), **Solubility of the Solutions of HFC-134a and Polyolester Based Oil,** *Energy Efficiency and Global Warming Impact* (proceedings of the meetings of Commissions B1 and B2, Ghent, Belgium 12-14 May 1993), International Institute of Refrigeration (IIR), Paris, France, 141-148, 1993 (8 pages with 5 figures and 2 tables, RDB5310)

R-134a, polyolester (POE) lubricant

please see page 6 for ordering information

M. Tanaka, T. Hayashi, K. Takeuchi, K. Takahata, and N. Sakamoto (Mitsui Petrochemical Industries, Limited, Japan), **New Non-POE Lube Oil with Low Viscosity for Refrigerators**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 291-296, July 1996 (6 pages with 2 figures and 5 tables, RDB6919)

synthetic, ether-type lubricant (Mitsui RE-5210) for use with R-134a; thermal stability determined with a differential scanning calorimeter; thermal decomposition and oxidation temperatures for RE-5210, an unidentified polyolester (POE), and a naphthenic mineral oil (Witco Suniso® 4GS); chemical stability comparisons of RE-5210 to the POE and a naphthenic mineral oil (Witco Suniso® 3GS), the latter with R-12; compatibility with polyethylene terephthalate (PET); lubricity by Falex and four-ball tests; water absorption; properties

R. H. P. Thomas and H. T. Pham (AlliedSignal Incorporated), **Solubility and Miscibility of Environmentally Safer Refrigerant-Lubricant Mixtures,** paper AN-92-5-1, *Transactions* (Winter Meeting, Anaheim, CA, January 1992), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 98(1):783-788, 1992 (6 pages with 9 figures and 1 table as RDB-2101)

Solubility and miscibility data are presented for R-134a with two polyalkylene glycol (PAG) lubricants (AP-150 and AP-500) and three modified PAGs (BRL-150, BRL-300, and BRL-500). Solubility was determined by measuring the equilibrium vapor pressure of mixtures of 10-90% refrigerant (by weight) in the lubricants for 10-70 °C (50-158 °F). Miscibility was determined by visual observation of a sealed sample immersed in a thermostatted bath for a range of -60 to 70°C (-76 to 158 °F). Differences in miscibility curve characteristics are contrasted to mineral oils. The paper examines occurrence of lower critical solution temperatures (LCSTs). Similarities of refrigerant-oil systems to solvent-polymer solutions are addressed, leading to correlations of the solubility data using the Flory-Huggins theory. While further analysis is indicated, Flory-Huggins type plots allow deduction of composition in a refrigerant-lubricant system, given the temperature and pressure and assuming equilibrium.

R. H. P. Thomas, R. P. Robinson, R. H. Chen, and W-T. Wu (AlliedSignal Incorporated), **The Solubility of R-32/125 in Modified Polyalkylene Glycols,** *Proceedings of the International CFC and Halon Alternatives Conference* (Baltimore, MD, 3-5 December 1991), Alliance for Responsible CFC Policy, Arlington, VA, 375-383, 1991 (9 pages with 2 figures and 2 tables, RDB2228)

This paper provides solubility data on a mixture of 60.32% R-32 and 39.68% R-125, by weight, with two synthetic lubricants. This nonsegregating refrigerant blend is proposed as a candidate replacement for R-22 in medium- and high-temperature applications, with evaporator temperatures of -23 to 4 °C (-10 to 40 °F). The lubricants examined were a modified polyalkylene glycol (PAG) and a PAG diol, BRL-150 and AP150 respectively. Tests also were made with mineral oils and alkylbenzene lubricants, but the refrigerant mixture was found to be immiscible with them. By contrast, the refrigerant was found miscible in the two PAGs from -60 to at least 55 °C (-76 to 131 °F). The same lubricants also are suitable for use with R-134a. The miscibility of the refrigerant-lubricant mixture was determined by sealing samples in thermostatted glass tubes and visually observing the contents. The solubility was studied by determining the equilibrium vapor pressure at constant compositions as a function of temperature. The experimental apparatus and procedure is described. Measured vapor-pressures are tabulated, compared to earlier data, and extrapolated using Flory-Huggins theory. The relative pressure is tabulated at different temperatures for fixed fractions of lubricant by volume for verification. Plots are provided for both pressure and relative pressure versus volume fraction of lubricant, from 0.0 to 1.0, for R-32/125 in the modified PAG. The text observes that the solubility for the PAG diol is of the same order.

R. H. P. Thomas, W-T. Wu, and H. T. Pham (AlliedSignal Incorporated), **The Solubility and Viscosity of Mixtures of R-134a with Modified Polyglycols,** paper 48, *New Challenges in Refrigeration* (proceedings of the XVIIIth International Congress of Refrigeration, Montreal, Québec, Canada, 10-17 August 1991), International Institute of Refrigeration, Paris, France, 11:412-415, August 1991 (4 pages with 7 figures, RDB2229)

The solubilities and viscosities of mixtures of R-134a with two modified polyalkylene glycol (PAG) lubricants are reported. The piston-cylinder type viscometer and apparatus for measuring solubility are described. The solubility of R-134a in BRL-150 (a 150 SUS experimental lubricant) is plotted for 10-70 °C (50-158 °F) in concentrations of 0-100%. Its viscosity in BRL-150 and BRL-300 (300 SUS) is plotted both as functions of temperature for -20 to 80 °C (-4 to 176 °F) and pressure. Analysis of the solubility shows that it can be described by the Flory-Huggins theory.

R. H. P. Thomas, W-T. Wu, and H. T. Pham (AlliedSignal Incorporated), **Solubility and Viscosity of R-134a Refrigerant-Lubricant Mixtures**, *ASHRAE Journal,* 33(2):37-38, February 1991 (2 pages with 3 figures, RDB2230)

U. Todsen, **Refrigerating Machinery Oil - Better Performance with Synthetic Lubricants? Investigations Concerning Thermal Stability of Refrigerator Oils**, *Ki Klima-Kälte-Heizung,* Germany, 15(4):186-189, April 1987 (4 pages in German, rdb-4C32)

This article reviews the requirements for lubricants for trouble-free refrigerator operation. It examines commercially-available oils and summarizes an investigation into their thermal stability.

J. C. Tolfa, **Synthetic Lubricants Suitable for Use in Process and Hydrocarbon Compressors**, *Lubrication Engineering,* 47(4):289-295, April 1991 (7 pages, rdb4C40)

S. I. Tseregounis (General Motors Corporation), **Wear and Galling of 356-T6 Aluminum-on-Steel in Low Amplitude Reciprocating Sliding in the Presence of Synthetic Lubricants in HFC-134a Atmosphere**, paper 95-AM-1C-1 (50th Annual Meeting, Chicago, IL, 14-19 May 1995), Society of Tribologists and Lubrication Engineers (STLE), 1995 (12 pages with 15 figures and 4 tables, RDB5A08)

This paper presents bench tests of wear and galling of aluminum (A356-T6) against steel (SAE 4620 carburized) in refrigerant-lubricant atmospheres. The tests were performed using a Falex test machine, modified to provide low-amplitude reciprocating motion with 5° oscillation, in a block-on-ring test arrangement. R-12 was examined with a mineral oil (GM M100), containing minimal antioxidant, as a reference. R-134a was tested with seven lubricants including the same mineral oil, five polyalkylene glycols (PAGs), and a polyolester (MO2D) containing tricresyl phosphate (TCP) and antiwear and extreme pressure (EP) additives. The PAG lubricants included a 50/50 ethylene oxide/propylene oxide, butanol initiated polyglycol (50HB); the same base stock with phosphate and triazole-derivative antiwear additives and amine corrosion inhibitors (U8); an esterified polypropylene oxide glycol (D1); and additized version (G551) of it; and a blended polyglycol (B0354). Of these, M100 and U8 are indicated to be the factory fill used in production of R-12 and R-134a automotive air conditioners, respectively. The paper summarizes background studies, wear mechanisms, preventive measures, and the experimental details. The test arrangement Is shown schematically. The paper then identifies the materials tested in tables and presents the investigation. The extents of galling and wear are shown in plots, photographs, SEM analyses, and electron microprobe (EMP) analyses. The R-12/M100 case resulted in the lowest wear and almost no galling, attributed to formation of halide (mainly chloride) antiwear and EP films that protect the aluminum surface. The R-134a/M100 case also resulted in low wear and galling, possibly because the low solubility of R-134a in the oil prevented removal of the lubricant film. High wear and galling with R-134a is attributed to the absence of oil or antiwear films. The paper notes that fluorine-containing films do not offer any protection against wear and galling under the conditions examined. It concludes that the presence of a lubricant film and/or EP or antiwear films (chlorides primarily) prevent metal-to-metal contact and damage of the aluminum surface.

S. I. Tseregounis and M. J. Riley (General Motors Corporation), **Solubility of HFC-134a Refrigerant in Glycol-Type Compounds: Effects of Glycol Structure**, *AIChE Journal,* 40:726 ff, 1994 (rdb7643)

R-134a/PAG, polyalkylene glycol, refrigerant lubricant properties

K. Ueshima (ICI, Japan), **Properties of Polyol Ester Oil and Examples of Retrofit Applications**, paper 5.2, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 107-112, December 1994 (6 pages with 3 figures and 6 tables; in Japanese with abstract, figures, and tables in English; RDB5420)

R-22, 32, R-134a, R-502, R-407A, R-407B, R-407C, polyolester (POE), retrofit, viscosity, refractive index, compatibility with elastomers, performance

N. A. Van Gaalen, S. C. Zoz, and M. B. Pate (Iowa State University of Science and Technology), **The Solubility and Viscosity of Solutions of R-502 in a Naphthenic Oil and in an Alkylbenzene at High Pressures and Temperatures,** paper 3519 (580-RP), *Transactions* (Annual Meeting, Indianapolis, IN, 22-26 June 1991), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 97(2):285-292, 1991 (8 pages with 14 figures and 2 tables, RDB2344)

N. A. Van Gaalen, S. C. Zoz, and M. B. Pate (Iowa State University of Science and Technology), **The Solubility and Viscosity of Solutions of HCFC-22**

please see page 6 for ordering information

in a Naphthenic Oil and in Alkylbenzene at High Pressures and Temperatures, paper 3446 (580-RP), *Transactions* (Winter Meeting, New York, NY, 19-23 January 1991), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 97(1):100-108, 1991 (9 pages with 15 figures and 2 tables, RDB5548)

solubility and viscosity of R-22 with a commonly-used, 150 SUS, naphthenic mineral oil (MO) and a 150 SUS alkylbenzene lubricant: presents measurements for mixtures of 10-40% R-22 by mass for 38-149 °C (100-300 °F); provides empirical correlations of these data and compares the findings to previously published data

N. A. Van Gaalen, S. C. Zoz, and M. B. Pate (Iowa State University of Science and Technology), **The Solubility and Viscosity of Solutions of HCFC-22 in Naphthenic Oil and in Alkylbenzene at High Pressures and Temperatures**, *Transactions* (Annual Meeting, St. Louis, MO, 9-13 June 1990), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 96(2):100-108, 1990 (9 pages with 15 figures and 2 tables, rdb2232)

laboratory measurements of the solubility and viscosity for R-22 with two commonly-used 150 SUS lubricants: reports results for liquid mixtures of 10-40% m/m R-22 in a naphthenic mineral oil (MO) and in an alkylbenzene (AB) for 38-149 °C (100-300 °F); presents a nonlinear regression analysis that provides empirical correlations of these data; reports reasonable agreement with the limited published data

J. N. Vinci and D. L. Dick (Lubrizol Corporation), **Polyol Ester Lubricants for HFC Refrigerants: A Systematic Protocol for Additive Selection**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 78-86, October 1995 (9 pages with 4 figures and 6 tables, available from JMC as RDB5A48)

polyolester (POE), synthetic ester, thermal stability, wear, hydrolytic stability, desiccant compatibility, capillary tube blockage, endurance capillary tube flow, miscibility, antiwear, load bearing

F. P. Wardle, B. Jacobson, H. Dolfsma (SKF Engineering & Research Centre B.V, Nieuwegein, The Netherlands), E. Höglund, and U. Jonsson (University of Luleå, Sweden), **The Effect of Refrigerants on the Lubrication of Rolling Element Bearings Used in Screw Compressors,** *Proceedings of the 1992 International Compressor Engineering Conference at Purdue*, edited by J. F. Hamilton, Purdue University, West Lafayette, IN, 11:523-534, July 1992 (12 pages with 20 figures and 1 table, RDB5A04)

R-22 and naphthenic mineral oil; R-134a and two polyolester lubricants

F. P. Wardle, B. Jacobson, and H. Dolfsma, **Rolling Bearing Lubrication in the Presence of Refrigerants**, unpublished paper for the SRM Licensee Conference (Stockholm, Sweden), SKF Engineering & Research Centre B.V, Nieuwegein, The Netherlands, May 1992 (10 pages with 12 figures, R DB5A05)

This paper reviews the lubrication parameters that influence rolling-bearing performance and examines the effect of refrigerant on the lubricant film thickness and performance. It briefly reviews the differences in lubrication requirements for hydrodynamic and rolling bearings. The paper then outlines the operating characteristics of rolling bearings, with attention to the stresses induced at contacting surfaces and fatigue life. The latter is presented as a ratio of minimum film thickness to composite surface roughness. The paper discusses the rheological properties of lubricants, addressing the dependence of viscosity on both temperature and pressure. A formula is presented for lubricant film thickness based on dimensionless speed, materials, load, and surface size parameters. The paper then describes a test rig built to simulate bearing operating conditions in a screw compressor; the apparatus and a detail of the bearing test head are shown schematically. The paper presents and discusses typical refrigerant concentration in the rig's lubricant "bath" (sump), the refrigerant concentration normalized to the equilibrium concentration based on pressure-temperature-solubility data, and the comparative viscosity of a naphthenic mineral oil and R-22/oil mixture as a function of pressure. It then explains the effect of refrigerant on the pressure-viscosity coefficient and on the viscosity of the lubricant. The effective viscosity is plotted for R-22 with a mineral oil and for R-134a with an unidentified polyolester lubricant, as functions of the refrigerant concentrations. The paper concludes that the thickness of lubricant films can be predicted at the highly-stressed contacts in rolling bearings. For oil rich (less than 20% refrigerant by weight) solutions, the primary effect of the refrigerant is viscosity reduction. The reduction in the pressure-viscosity coefficient becomes progressively more significant as the refrigerant concentration increases. Performance also depends on whether a single or multiple phases are present, the refrigerant-lubricant temperature, and the pressure.

Mark C. Watson (CPI Engineering Services, Incorporated, UK), J. E. Oberle, and T. E. Rajewski (CPI Engineering Services, Incorporated, USA), **Lubricants for Natural Working Fluids**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 458-467, 1998 (10 pages with 2 figures and 4 tables, RDB9250)

tabulates physical properties for naphthenic and paraffinic mineral oils (MO), hydrotreated paraffinic lubricants, and synthetic lubricants; summarizes their characteristics as well as those of polyalphaolefins (PAO), polyolesters (POE), and polyglycols including polyalkylene glycols (PAG); discusses polyglycols including polypropylene glycols (PPG) for use with hydrocarbons, R-717 (ammonia), and R-744 (carbon dioxide); compares the miscibility and mineral oil solubility of five ammonia soluble lubricants; tabulates pin-and-vee-block wear test results for those lubricants; concludes that optimized lubricants offering improved heat transfer, efficiency. low-temperature properties, lubricant longevity, and greater flexibility are available for ammonia and hydrocarbons to replace traditional mineral oils; notes that lubricant options including polyglycols and POEs are being evaluated for use with carbon dioxide; includes discussion by F. Broesby-Olsen (Danfoss A/S, Denmark), B. Adamson (Refrigeration Engineering Pty Limited, Australia), and D. Osbourne (UK)

C. L. Wellman and R. W. Yost (ICI Klea), **The Solubility of Refrigerant Blends in Synthetic Polyol Ester and Alkylbenzene Refrigeration Lubricants and the Effect of Viscosity,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 68-77, October 1995 (10 pages with 10 figures and 1 table, available from JMC as RDB5A47)

R-22, R-32, R-125, R-134a, R-407C, R-410A , polyolester (POE, ICI Emkarate® RL) and alkylbenzene (AB) lubricants

S. Yokoo, K. Doi, T. Takano (Nissan Motor Company, Limited, Japan), and T. Kaimai (Kyodo Oil Technical Research Center Company, Limited, Japan), **Development of a Lubricant for Retrofitting Automotive Air Conditioners for Use with HFC-134a,** *Climate Control and Automotive Cabin Air Filtration,* publication SP-1040, Society of Automotive Engineers (SAE), Warrendale, PA, 57-61, 1994; republished as paper 940594 (SAE International Congress and Exposition, Detroit, MI, 28 February - 3 March 1994), SAE, 1994 (8 pages with 4 figures and 5 tables, RDB4B01)

This paper introduces a new lubricant for use with R-134a, for retrofit of mobile air-conditioning (MAC) systems originally designed for R-12 with mineral oils. The lubricant is described as a block polymer polyalkylene glycol (PAG). The paper briefly reviews the introduction of R-134a for use in new and retrofit MAC applications. It notes that the chlorine in R-12 helps to lubricate compressors, by acting as an extreme pressure (EP) agent. Consequently, retrofit with chlorine-free R-134a requires a lubricant with high enough lubricity to compensate for this lack of a lubricating agent. Moreover, the lubricant also must be suitable in the retrofit environment. The paper indicates that antiwear additives in the retrofit lubricant may transfer to residual mineral oil, thereby reducing lubricity since the mineral oil would be insoluble in R-134a. Further, residual R-12 or moisture may degrade the chemical stability of PAG lubricants. Metal chlorides formed from prior operation with R-12 may be hydrolyzed by moisture from the lubricant, producing hydrochloric acid and resultant chemical attack. The paper outlines the development of the new lubricant specifically for wobble-plate, variable displacement compressors. A table compares the structures, lubricity, hygroscopicity, and R-134a miscibility of three PAG classes comprising alkyl, propylene oxide, and ethylene oxide groups. It also discusses use of a benzotriazole (BTA) derivative, as an antiwear additive and corrosion preventive agent to protect copper alloys. The antiwear effect is attributed to adsorption of the BTA element on copper surfaces and to the friction-reducing action of the long-chain alkyl groups, which form the oil film. Figures show pin and bearing wear as functions of the BTA quantity added in Falex pin and v-block tests and compressor tests. Oiliness and phosphate additives, to protect aluminum anti-rotation mechanisms, also are discussed. The use of an organic molybdenum compound as an EP agent was tested, but not selected to avoid degradation of the lubricant stability. Acceptance criteria and data on compatibility with organic materials, based on sealed-tube and autoclave tests, are tabulated for the new lubricant.

B. Yudin, M. Boiarski, and C. S. Munday, **Influence of HCFC and Hydrocarbon Components in Blend Refrigerants on Oil-Refrigerant Miscibility,** *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 106-114, November 1997 (9 pages with 8 figures and 1 table, RDB8333)

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analysis of the quantity and nature of lubricant-miscible components on blend miscibility with mineral oil based on liquid-liquid equilibrium: presents comparisons for blends incorporating R-134a, including R-416A, with a naphthenic mineral oil (MO, Witco Suniso® 4GS); InterCool Energy's product name for R-416A is FRIGC™ FR-12, marketed as a replacement for R-12 in mobile air conditioning (MAC) systems

V. P. Zhelezny, Y. V. Semeniuk, D. A. Vladimirov, O. G. Reminyak (Odessa State Academy of Refrigeration, Ukraine), and M. V. Rybnikov (Odessa State Academy of Food Technology, Ukraine), **Phase Equilibrium, Density, and Miscibility of Quasi-azeotropic Mixtures HFC152a/HFC134a in Refrigeration Oils**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:630-637, 1995 (7 pages with 4 figures and 2 tables, rdb-6C29)

R-134a/152a (80/20 mol/mol), near-azeotropic blends, refrigerant-lubricant properties with a polyether oil (Xϕ-22c-16) and a synthetic polyoxyalceleneglycolic lubricant (Xϕ-134), thermodynamic properties, thermophysical data

S. C. Zoz and M. B. Pate (Iowa State University of Science and Technology), **Critical Solution Temperatures for Ten Different Non-CFC Refrigerants with Fourteen Different Lubricants**, *Proceedings of the 1994 International Refrigeration Conference at Purdue,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 431-436, July 1994 (6 pages with 3 tables, RDB4858)

S. C. Zoz, L. J. Berkenbosch, and M. B. Pate (Iowa State University of Science and Technology), **Miscibility of Seven Different Lubricants with Ten Different non-CFC Refrigerants,** paper 3802, *Transactions* (Annual Meeting, Orlando, FL, 25-29 June 1994), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 100(2):197-207, 1994 (11 pages with 2 figures and 11 tables, RDB4715)

miscibility data for R-22, R-32, R-123, R-124, R-125, R-134, R-134a, R-142b, R-143a and R-152a with naphthenic mineral oil (MO), alkylbenzene (AB), and polyalkylene polyol (PAG), and polyolester (POE) lubricants; refrigerant-lubricant (RL) properties

Moisture Content and Emkarate™ RL Ester Lubricants, bulletin 62-0170-160, ICI Americas Incorporated, Wilmington, DE, January 1994 (8 pages with 3 figures, RDB6B38)

introductory discussion of the hygroscopicity (affinity for moisture) of ester lubricants; plot of typical water absorption rate for polyolester (POE), polyalkylene glycol (PAG), modified PAG, and mineral oils; ways water enters refrigeration systems; water uptake; consequences including loss of performance, ice deposition, corrosion of metals, blockage of expansion devices, copper plating, and poor lubrication; hydrolysis; water pull-down (drying) rates for ester and PAG lubricants with driers; handling and housekeeping recommendations

Real Time Determination of Lubricant Concentrations Dissolved in Alternative Refrigerants, research project 761-RP, American Society of Heating, Refrigerating, Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1996 - December 1996, extended to 1998 (ASH0761) .

This project will evaluate three means of measuring the concentration of lubricants circulating in refrigeration systems. The apparatus to be addressed include a viscometer, a densimeter, and an acoustic velocity sensor. The project is a follow-up to a prior project, *Real Time Determination of Concentration of Oil Dissolved in Refrigerant Flow Stream Without Sample Removal* (365-RP, see ASH0365), completed in January 1988. Three alternative refrigerants will be evaluated, including R-123, R-134a, and a third to be determined. Each will be tested with two lubricants in concentrations of 0-6% at temperatures representative of condenser outlets, namely 24-49 °C (75-120 °F). The contractor for the project is Imagination Resources, Incorporated (IRI), led by R. C. Cavestri; it is sponsored by ASHRAE Technical Committee 1.2, *Instruments and Measurements.*

Refrigeration Compressor Lubrication with Synthetic Fluids, publication 801201, Mobil Oil Corporation, Fairfax, VA, 1980 (40 pages with 28 figures and 4 tables, RDB3510)

This bulletin reviews the fundamentals of refrigeration systems, discusses the roles of lubricants, identifies benefits of synthetic lubricants, and provides data on Mobil lubrication products. The introduction discusses the attributes sought in a lubricant and comparative qualities of conventional mineral oils (MOs), synthesized hydrocarbon fluids (SHFs), and polyglycols. It notes that low viscosity, naphthenic MOs have dominated to meet the need for low pour points, but that the final viscosity is lower than for the neat lubricant due to refrigerant dilution. The synthetic lubricants can be selected for specific refrigerants and applications with fluidity over a wide range, not encumbered by wax content at low temperatures, and high viscosity index (VI). The effects of refrigerant solubility in lubricants on viscosity, vapor pressure, and specific gravity as well as refrigerant-lubricant system performance are discussed. The bulletin reviews refrigeration cycles, common refrigerants, system components, and the roles of lubricants in wear reduction and sealing. It provides solubility plots of R-12, R-13, R-13B1, and R-22 in mineral oil; R-22 in mineral oil, SHF, and polyglycol; and R-290 (propane) in a polyglycol. It then provides a series of plots to show the estimated viscosity-diluting effect of refrigerants in lubricants. They include plots for R-12 with Gargoyle Arctic SHC 226, SHC 230, and Glygoyle 80; R-22 with SHC 226, SHC 234, and Glygoyle 11; R-114 with Gargoyle Arctic SHC 230 and SHC 234; and R-290 with Mobil Glygoyle 30. The report discusses solubility and miscibility, noting that the lubricating fluid in the compressor is a solution of refrigerant vapor in lubricant. In other parts of the system, such as the condenser, the fluid may be a solution of lubricant in liquid refrigerant. Thus the mixture may be in two phases, termed "mutual solubility," which is the basis for classification as completely miscible, partially miscible, and immiscible. The report describes miscibility characteristics and identifies typical miscibility in mineral oils for R-11, R-12, R-13, R-13B1, R-14, R-21, R-22, R-113, R-114, R-115, R-152a, R-C318, R-500, R-501, R-502, R-717, and R-744. It discusses and provides miscibility plots for mineral oil, polyglycol, and SHF with R-22 and for polyglycol with R-12, R-13, R-13B1, and R-290. It then briefly discusses floc and cloud points, specific gravities of refrigerant-lubricant mixtures, stability of lubricants, VI and cold starting, copper plating, and compatibility. It also discusses lubricant influences on power consumption and describes applications in compressors, reliquification systems, and heat pump systems. The report concludes with a summary of Mobil lubricant products, including tables of physical characteristics and recommended type(s). An appendix provides a trouble shooting guide for lubricants. Mobil's product names are Gargoyle Arctic Oil for mineral oils, for Gargoyle Arctic SHC for SHFs, and Mobil Glygoyle for polyglycols.

Solubility of R-123 and R-134a in Oils, Carrier Corporation, Syracuse, NY, September 1989 (3 pages with 3 figures, available from JMC as RDB-0014)

Two figures summarize the solubility of R-123 with Mobil DTE 26 and Mobil DTE Heavy Medium mineral oils for -29 to -23 °C (-20 to -10 °F). Critical solution temperatures are shown for solutions of 70-95% R-134a in unidentified 300 and 750 SUS polyglycol lubricants.

Solubility of Refrigerant in Lubricants: HFC-134a, report NIST-3, Freon® Products Laboratory, E. I. duPont de Nemours and Company, Incorporated, Wilmington, DE, undated circa 1989 (3 pages with 2 tables, available from JMC as RDB0533)

Solubility data for R-134a are presented for a range of lubricants based on tests run from -50 to 93 °C (-58 to 199 °F). Mixtures of 30, 60, and 90% refrigerant by weight were tested with the lubricants in air-free sealed tubes. Solubility was determined, following a minimum of 15 minutes with agitation at each temperature; the blends were considered immiscible when they acquired and retained *schlieren* lines, formed floc, or formed two liquid layers. The lubricants include a polychlorotrifluoroethylene (Halocarbon blend 700/95-6.7/93.3 500 SUS), four perfluorinated polyalkyl ether oils (Krytox® GPL 150 and 480 SUS and Fomblin® Y 25/5 and Z15, both 417 SUS), and Daikin Demnum® S-65 300 SUS), dipentaerythritol esters of fatty acids (Hercules 240 and 290 SUS), PEG esters of fatty acids (CPI Engineering 144, 620, and 830 SUS), naphthenic oils (Witco Suniso® 5GS 500 SUS 38% aromatic, Witco 500 SUS and two experimental oils at 520 SUS 47% aromatic and 529 SUS 75% aromatic), paraffinic oil (BVM-100N 500 SUS), three alkylbenzenes (Zerol® 300 SUS, Conoco DN600 125 SUS, and Nippon Oil Atmos HAB15F 78 SUS), and three silicone oils (Union Carbide L-45 163, 231, and 462 SUS).

Study of the Segregation or Fractionation of Refrigerant Blends in Contact with Lubricants and Measurement of Viscosity, Solubility, and Density, research project 779-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1995 - April 1996, extended to 1998 (ASH0779)

This project will measure the solubility, viscosity, and density of refrigerant blends comprising hydrofluorocarbons (HFCs) with a representative lubricant. An additional objective is to determine the influence, if any, of the lubricant on segregation and fractionation of the refrigerant mixtures. R-32, R-134a, R-32/134a (30/70), and R-32/134a (70/30) will be examined with a 32 ISO polyolester lubricant in compositions of 0-100%, vapor pressures of 70-2350 kPa (10-500 psia), and -40 to 125 °C (-40 to 257 °F). The miscibility and composition, in the gas and liquid phases (dissolved in the lubricant or as a separate liquid phase), of the cited fluids and of R-134a also will be measured. The results will be plotted. The contractor is Imagination Resources, Incorporated (IRI), led by R. C. Cavestri; the project is sponsored by ASHRAE Technical Committees 3.4, *Lubrication,* and 8.1, Positive *Displacement Compressors*.

please see page 6 for ordering information

APPLICATION DATA

R. C. Downing (Consultant, formerly DuPont Chemicals), **Fluorocarbon Refrigerants Handbook**, Prentice Hall, Englewood Cliffs, NJ, 1988 (416 pages with 124 figures and 177 tables, RDB3960)

This popular handbook provides a general review of refrigerants and application data. It briefly outlines the history, nomenclature, manufacture, and applications of fluorocarbon refrigerants and then covers refrigeration, refrigerant properties, and mixtures (including azeotropes). It continues with the effects of water including solubility, drying, and hydrolysis; solubility of air and other gases; oil relationships including solubility and viscosity; the effects on polymers including both elastomers and plastics; and stability. It also addresses leak detection, solar applications (as heat transfer fluids), conversion factors, shipping data, and safety parameters and classifications. A final chapter provides pressure-enthalpy (Mollier) diagrams for R-11, R-12, R-13, R-13B1, R-14, R-21, R-22, R-113, R-114, R-115, R-C318, R-502, and R-503. It also provides equations to calculate liquid density; vapor pressure; pressure-volume-temperature (PVT) data (equations of state); heat capacity, enthalpy, and entropy of the vapor; velocity of sound; and latent heat of vaporization for R-11, R-12, R-13, R-14, R-21, R-22, R-23, R-113, R-114, R-C318, R-500, and R-502.

L. A. Orth, D. C. Zeitlow, and C. O. Pedersen (University of Illinois at Urbana-Champaign), **Predicting Refrigerant Inventory of R-134a in Air-Cooled Condensers**, paper CH-95-23-1, *Transactions* (Winter Meeting, Chicago, IL, 28 January -1 February 1995), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(1):1367-1375, 1995 (9 pages with 7 figures and 1 table, RDB5240)

R-134a

Refrigerants & Service Pointers Manual, bulletin E-37166, edited by R. C. Downing, E. I. duPont de Nemours and Company, Incorporated, Wilmington, DE, 1970 republished May 1986 (78 pages with 41 figures and 25 tables, RDB5C49)

R-11, R-12, R-13B1, R-21, R-22, R-113, R-114, RC318, R-500, R-502, history, application, materials compatibility, properties, stability, safety, pressure drop, density, color coding, evacuation, water effects, drying, service recommendations, brazing and soldering, motor burnouts, charging refrigerants

Fractionation Leakage and Detection

F. R. Biancardi, D. R. Pandy, T. H. Sienel, and H. H. Michels (United Technologies Research Center, UTRC), **Modeling and Testing of Fractionation Effects with Refrigerant Blends in an Actual Residential Heat Pump System**, paper PH-97-9-5, *Transactions* (Winter Meeting, Philadelphia, PA, 26-29 January 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 103(1):781-794, 1997 (14 pages with 14 figures and 1 table, RDB7C18)

F. R. Biancardi, H. H. Michels, T. H. Sienel, and D. R. Pandy (United Technologies Research Center, UTRC), **Investigation into the Fractionation of Refrigerant Blends**, report DOE/CE/23810-75 (also identified as UTRC R95-970566-5), Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, January 1996 (244 pages with 98 figures and 6 tables, available from JMC as RDB7650; some of the figure and table headings are partially cut off)

This report summarizes analyses and measurements of composition changes in hydrofluorocarbon (HFC) refrigerant blends. It presents a model (NISC), verified by laboratory data, to predict the fractionation effects of HFC blends exposed to selected polyolester (POE) lubricants, during system charging from large liquid containers, and for selected leakage modes. The model is based on nonideal, Wohl solution theory for lubricant-solubility effects. The model also predicts the effects of system startup, operation, and shutdown for system components where two-phase refrigerant exists, notably the heat exchangers, expansion valve, and compressor sump. The report notes that blend fractionation can increase hazards if the more or most volatile component is flammable and a leak occurs. Fractionation also can change component or system performance and cause unacceptable, higher system pressures. The work comprised four tasks, namely to investigate lubricant solubility effects, fractionation effects from successive charges, fractionation within system components, and fractionation during leaks. Findings are presented for R-32/134a (25/75), identified in the report as *Blend A,* and for R-407C [R-32/125/134a (23/25/52)]. The report notes that R-407C is much less sensitive to fractionation than R-32/134a (25/75) and that the latter zeotrope is has a greater potential for flammable concentrations when the system is idle at low temperatures and during startup. Such leakage impacts performance even when losses are replaced with the original composition, due to preferential leakage of R-32. Both modelled and experimental findings indicate that the circulating composition changes when there is a significant quantity of refrigerant in the accumulator or elsewhere in the refrigerant circuit. The findings also indicate that the oil absorbs some of the refrigerant and contributes to fractionation by preferential absorption of R-134a, but that no extremes in temperature or pressure result from fractionation within the system; similarly, capacity and performance change only slightly.

D. B. Bivens, M. B. Shiflett, C. C. Allgood, and A. Yokozeki (DuPont Fluoroproducts), **Zeotropic Mixture Separations Analyses**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 113-118, July 1996 (6 pages with 10 figures, RDB-6820)

thermodynamic model to simulate a slow vapor leak, comparison to experimental data for R-401A, R-404A, R-407C, R-125/143a (45/55); comparison to NIST REFLEAK model for R-401A and R-407C

D. Cal, **Escape of Hydrocarbon Refrigerants in Car Air Conditioning**, M.Eng.Sc. thesis (School of Mechanical and Manufacturing Engineering), University of New South Wales, Sydney, Australia, 1996 (121 pages, rdb8357)

prediction of maximum refrigerant concentrations from leakage of R-290/600a (50/50) into cars

F. C. Chen, S. L. Allman, and C. H. Chen (Oak Ridge National Laboratory, ORNL), **New Concepts for Refrigerant Leak Detection and Mixture Measurement**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC), Alliance for Responsible CFC Policy, Arlington, VA, 211-217, October 1993 (7 pages with 4 figures, RDB3A44)

D. Clodic and M. Ben Yahia (École des Mines de Paris, France), **New Test Bench for Measuring Leak flow Rate of Mobile Air Conditioning Hoses and Fittings,** *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 385-391, November 1997 (7 pages with 4 figures and 3 tables, rdb8353)

laboratory test method to determine the leak rate of hoses, crimped connections between the hose and fitting, and fittings for mobile air-conditioning (MAC) and transport refrigeration systems: estimates annual losses for MAC systems to be 0.15-0.40 kg/yr (0.3-0.9 lb/yr) for MAC systems with approximately 300 million in service and half that number in the United States

S. Esslinger, **The True Cost of Refrigerant Leaks,** *ASHRAE Journal,* 30(11):27-29, November 1988 (3 pages with 1 figure and 2 tables, RDB4237)

analysis of efficiency losses resulting from refrigerant leaks in supermarket refrigeration systems; identifies vibration transmitted by piping, movement of compressors, and pressure pulsations as the most frequent causes; recommends design and preventative maintenance measures to minimize losses

C. L. Gage (U.S. Environmental Protection Agency, EPA) and E. F. Troy (HEC, Incorporated), **Reducing Refrigerant Emissions from Supermarket Systems**, *ASHRAE Journal,* 40(11):32-33 and 35-36, November 1998 (5 pages with 1 figure and 1 table, RDB8C02)

presents data on and measures to reduce refrigerant losses from commercial refrigeration systems: notes that the average annual loss rates in 1993 for 36 stores from a sample of 41 was 14% for R-12 and 13% for R-502 and that approximately 25% had annual losses exceeding 20%; also presents a summary of service data for a supermarket chain with 110 stores; the tabulated data identify the component or subsystem requiring service and resulting refrigerant losses; identifies options in design, construction, operations, maintenance, and corporate policies and practices to reduce total charge and loss rates

M. R. Harrison (Radian Corporation), R. C. Keeney (Jones Nuese), and T. P. Nelson (Radian Corporation), **Pilot Survey of Refrigerant Use and Emissions from Retail Food Stores**, paper 3835, *Transactions* (Winter Meeting, Chicago, IL, 28 January -1 February 1995), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(1):25-33, 1995 (9 pages with 6 tables, RDB5231)

R-12, R-22, R-502

N. J. Hewitt, J. T. McMullan, and B. Mongey (University of Ulster, UK), **The Replacement of HCFC 22 in Refrigeration Systems,** *CFCs, the Day After* (proceedings of the IIR meeting, Padova, Italy, 1994), International Institute of Refrigeration (IIR), Paris, France, 231-237, September 1994 (7 pages with 6 figures, RDB8446)

tests of R-407C and R-32/125/134a (30/10/60) as R-22 replacements; concludes that manufacture of R-22 systems with polyolester (POE) lubricants in anticipation of future conversion to hydrofluorocarbon (HFC) refrigerants is undesirable since the high solubility of R-22 in POE lubricants lowers the oil viscosity, hampers its lubricating ability thereby, and reduces the overall system performance; shows that the differential solubility of the individual components

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of the R-407 series blends [and implied thereby also the R-410 series and potentially others] may shift the composition closer to or into the flammable range of the vapor refrigerant; illustrates the composition shift with a change for R-407C with a POE from R-32/125/134a (23/25/52) to R-32/125/134a (23.8/24.9/51.3), leading to a 5% loss in evaporator capacity and a vapor composition of (36/35/29) at the evaporator inlet for typical conditions based on a simplified analysis

M. S. Kim (Seoul National University, Korea) and D. A. Didion (National Institute of Standards and Technology, NIST), **Simulation of Isothermal and Adiabatic Leak Processes of Zeotropic Refrigerant Mixtures,** *HVAC&R Research*, 1(1):3-20, January 1995 (18 pages with 17 figures, RDB5201)

This article presents a study of the composition shifts of zeotropic blends during refrigerant leaks. The simulations addressed cover both slow and fast leaks, characterized by isothermal and adiabatic processes, respectively. The article summarizes interest in zeotropic blends and concerns such as fractionation to or of a flammable composition. Leak modes from container tops and bottoms, representing initial vapor and liquid leaks, are presented. The model is described as a quasi-steady state process with finite time increments, in each of which mass escapes and a new thermodynamic equilibrium is reached. The model uses the NIST REFPROP program to calculate refrigerant properties. The model is presented along with schematic diagrams of pressure and composition changes for both isothermal and adiabatic leaks. The results are illustrated with plots of mass fraction by component as a function of mass percentage lost. Results are shown for R-32/134a (30/70) and R-32/125/134a (30/10/60) for both vapor and liquid leaks. A sensitivity study shows the influence of temperature on leakage of the ternary mixture. The remaining fraction of the more or most volatile component decreases for either a vapor or liquid leak in the isothermal process. Also, the mass fraction changes at low temperature are greater than those at high initial temperature. The mass fraction of the more volatile component increases in the vapor and decreases in the liquid for the adiabatic process in both the vapor and liquid loss modes. The results show that the refrigerant left in the container remains nonflammable for both blends in isothermal vapor leaks, but could become flammable in the adiabatic process, since the R-32 fraction is highest in the final state. The authors note that the refrigerant charging process is close to the adiabatic process addressed, and that the model can be used to estimate the amount of refrigerant leaked from a system by measuring the pressure and using the equations presented.

H. H. Kruse (Universität Hannover, Germany) and F. Wieschollek (Forschungszentrum für Kälte- und Umwelttechnik GmbH, FKU, Germany), **Concentration Shift When Using Refrigerant Mixtures,** paper PH-97-9-1, *Transactions* (Winter Meeting, Philadelphia, PA, 26-29 January 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 103(1):-747-755, 1997 (9 pages with 11 figures and 5 tables, RDB7C14)

measurements and modeling of concentration shifts caused by internal fractionation of zeotropic blends: tests of R-407C and R-23/152a (20/80) in an air conditioner and water chiller, respectively; concentration shifts were analyzed for R-404A, R-407C, R-23/152a (20/80), and R-32/134a; influences of lubricant solubility on circulating concentration were examined for R-410A and R-507A with an ester oil without and with vapor leakage; concludes that while temperature glide causes a concentration shift only for zeotropic blends, differential lubricant solubility also leads to concentration changes for near-azeotropic and zeotropic blends; a computer model is under development to predict the concentration shift and resulting changes in performance

R. E. Low, B. E. Gilbert, M. Davies (ICI Klea, USA), J. D. Morrison, and F. T. Murphy (ICI Klea, UK), **Handling Zeotropic Refrigerants,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 216-224, October 1995 (9 pages with 2 figures and 1 table, available from JMC as RDB5A62)

azeotropes, zeotropes, glide, differential leakage, R-407A, R-407B, R-407C

I. L. Maclaine-cross (University of New South Wales, Australia), **Refrigerant Concentrations in Car Passenger Compartments,** *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 403-412, November 1997 (10 pages with 3 figures and 4 tables, RDB8356)

prediction of maximum refrigerant concentrations from leakage of R-290/600a (50/50) into cars: discusses failure modes leading to leaks and compares predicted and measured leaks into a car; examines ventilation rates and consequent peak concentrations; concludes that it is physically possible but still improbable that leaks will result in concentrations above the lower flammability limit (LFL) for four of ten cars tested; suggests precautions to reduce such risks

J. R. Parsnow, **Monitoring Instruments for HCFC-123**, publication 819-060, Carrier Corporation, Syracuse, NY, April 1992 (8 pages with 2 figures and 1 table, RDB2915)

R-123, leak detection

T. C. Sorensen (Thermal Gas Systems, Incorporated), **Seeking Out Chiller Leaks**, *Refrigerating Service and Contracting* (RSC), July 1995 (3 pages with 1 figure, limited copies available from JMC as RDB5C09)

This article provides an overview of refrigerant leak detection devices and their application. It cites the requirement for them in ANSI/ASHRAE Standard 15-1994, identifies data sources for detection levels, and outlines factors that facility managers, suppliers, and technicians need to know for installations. The article then describes common monitoring technologies including ceramic metal oxide semiconductor (CMOS) and infrared (IR) devices. It describes both and gives typical cost ranges. It then reviews instrument sensitivity, selectivity, speed of response, and location. It also describes two approaches, one that locates sensors where refrigerants are likely to concentrate and another that draws air samples to the sensor. The article concludes with recommended installation, calibration, and service practices.

S. Stanbouly and A. Wesolowski (York International Corporation), **Serviceability Issues Associated with R407C Refrigerant,** *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 125-132, July 1996 (8 pages with 10 figures, RDB6823)

R-407C, performance, leakage, fractionation: laboratory tests in a 10.6 kW cooling (3 ton) single-speed, split-system heat pump found a 3-4% decrease in capacity and performance in the cooling mode and 4-9% increase in capacity and 3-4% loss in efficiency in the heating mode; when 50% of the refrigerant charge was leaked by a simulated slow, isothermal leak and recharged to the nameplate amount, the capacity dropped 3-4% and efficiency by 5% due to a significant change in composition; the leaked gas is noted as rich in R-32, which is flammable; performance, service, design, manufacturing, and safety issues are outlined issues

Y. Sumida, T. Okazaki, T. Kasai (Mitsubishi Electric Corporation, Japan), and Y. Ueno (Mitsubishi Electric Engineering Company, Limited, Japan), **Composition Sensing Circuit for a Multiple Split Type Air Conditioner with R-407C**, *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 23, 1999 (9 pages with 9 figures and 1 table, RDB9875)

discusses the impact of changes in circulating mixture composition for a zeotropic refrigerant, R-407C, on the saturation temperature and pressure; describes a composition sensing (CS) circuit developed to enable precise control of R-407C systems with multiple indoor heat exchangers ("multiple split type" air conditioners); presents the basic principle of sensing the circulating composition and summarizes tests to measure is accuracy; paper concludes that the proposed CS approach detects the compositions of R-32, R-125, and R-134a to within ± 1, ± 1, and ±2% m/m, respectively; also concludes that the detection accuracy of condensing and evaporating temperatures are within ±½% and that the CS circuit offers an sufficiently accurate detection of transient compositions for practical use

Y. Sumida, N. Tanaka, and T. Okazaki (Mitsubishi Electric Corporation, Japan), **Prediction of the Circulating Composition of a Zeotropic Mixture in a Refrigerant Cycle,** *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:1013-1020, 1995 (8 pages with 4 figures, rdb7938)

theoretical analysis to predict the circulating composition of a zeotropic blend based on local equilibrium gas- and liquid-phase compositions: comparisons to experimental data for R-32/134a (30/70) show good agreement and that the more volatile component reaches a minimum composition fraction near the center of the evaporator; examination of capacity modulation by varying the amount of refrigerant in the accumulator concludes that it is possible for this blend without notable degradation in efficiency

S. G. Sundaresan and R. J. Watkins (Copeland Corporation), **Study of Liquid and Vapor Composition During Calorimetry,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 234-237, October 1995 (9 pages with 2 figures and 1 table, available from JMC as RDB5A64)

R-404A, R-407C, R-410A, fractionation of refrigerant blends during secondary calorimetry testing

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R. E. Tapscott and C. W. Sohn, **Halocarbon Refrigerant Detection Methods**, technical report 96/22, U.S. Army Corps of Engineers, Construction Engineering Research Laboratories, Champaign, IL, 1996 (available from GPO as document AES7492, rdb8267)

refrigerant leak detection

R. J. M. van Gerwen and B. J. C. van der Wekken (Netherlands Organization for Applied Scientific Research, TNO, The Netherlands), **Reduction of Refrigerant Emissions**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:782-789, 1995 (8 pages with 3 figures and 1 table, rdb7919)

field monitoring of emissions and determination of causes considering design, operation, and maintenance: annual losses before and after implementation of regulations for leak reduction were found to be 6% and 3%, respectively, in transport refrigeration systems and 15% and 3% for commercial refrigeration in supermarkets; discusses the Dutch regulations, identified leakage points, and detection of emissions

A. Yokozeki (DuPont Fluoroproducts), **Characteristics of Alternative Refrigerant Mixtures**, paper 1.3, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 12-16, December 1994 (5 pages with 12 figures and 3 tables; in Japanese with abstract, figures, and tables in English; RDB5403)

This paper examines the composition change and temperature glide of azeotropic and zeotropic refrigerant blends with and without oil present. It also addresses the oil viscosity and solubility of refrigerant-oil mixtures. The paper notes that azeotropic blends may undergo composition shifts due to differences in solubility of the components in lubricants. Pressure-composition plots depict the bubble and dew point curves at -30, 0, and 30 °C (-22, 32, and 86 °F) for R-22/115, R-125/143a, R-32/125, and R-32/134a. Plots illustrate the composition shifts of R-407C with vapor leakage and successive recharging. Four further plots show the vapor composition shift of R-407C, R-410B, R-502, and R-507A in unidentified polyolester (POE) lubricants. Two final figures show the viscosity-temperature-pressure-composition relations of R-407C and R-32/125 (60/40) with a POE. A table give the normal boiling point and maximum temperature glide (dew minus bubble point temperatures) for R-22, R-404A, R-407A, R-407B, R-407C, R-410A, R-502, R-507A, and R-32/134a (25/75) and (30/70). A second table contrasts the performance of R-22, R-410A, and R-410B. A final table shows the composition and pressure changes with 50% vapor leakage at 20 °C (68 °F) for R-404A, R-407C, R-410A, R-410B, R-502, R-507A, and R-32/134a (30/70).

Leak Detectors for Alternative Refrigerants, document ARTD-27 (H-31753-2), DuPont Chemicals, Wilmington, DE, December 1992 (8 pages, available from JMC as RDB4508)

Glide Matching and Lorenz Cycles

P. A. Domanski, W. J. Mulroy, and D. A. Didion (National Institute of Standards and Technology, NIST), **Glide Matching with Binary and Ternary Zeotropic Refrigerant Mixtures - Part 2: A Computer Simulation**, *Energy Efficiency and Global Warming Impact* (proceedings of the meetings of Commissions B1 and B2, Ghent, Belgium 12-14 May 1993), International Institute of Refrigeration (IIR), Paris, France, 354-363, 1993; republished in *International Journal of Refrigeration* (IJR), 17(4):-226-230, May 1994 (10/5 pages with 8 figures and 1 table, RDB5326)

R-22, R-142b, R-23/142b, R-23/22/142b, Lorenz cycle

W. J. Mulroy, P. A. Domanski, and D. A. Didion (National Institute of Standards and Technology, NIST), **Glide Matching with Binary and Ternary Zeotropic Refrigerant Mixtures - Part 1: An Experimental Study**, *Energy Efficiency and Global Warming Impact* (proceedings of the meetings of Commissions B1 and B2, Ghent, Belgium 12-14 May 1993), International Institute of Refrigeration (IIR), Paris, France, 343-353, 1993; republished in *International Journal of Refrigeration* (IJR), 17(4):220-225, May 1994 (11/6 pages with 7 figures and 1 table, RDB5327)

R-23/142b, R-23/22/142b, Lorenz cycle

Heat Transfer

T. A. Adamek and R. L. Webb (Pennsylvania State University), **Prediction of Film Condensation on Vertical Finned Plates and Tubes - A Model for the Drainage Channel**, *International Journal of Heat and Mass Transfer,* 33(8):1737-1749, 1990 (13 pages, rdb9802)

condensing heat transfer, enhanced condensers

D. M. Admiraal and C. W. Bullard (University of Illinois at Urbana-Champaign), **Experimental Validation of Heat Exchanger Models for Refrigerator Freezers**, paper 3836, *Transactions* (Winter Meeting, Chicago, IL, 28 January - 1 February 1995), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(1):34-43, 1995 (10 pages with 8 figures and 4 tables, RDB5232)

heat transfer

M. A. R. Akhanda and D. D. James, **Rib Orientation Effects on Heat Transfer Performance in Forced Convective Boiling**, *Chemical Engineering Communications*, 139:15-24, 1995 (10 pages, rdb9423)

heat transfer, surface enhancement

G. Akhilesh, J. S. Saini, and H. K. Varma, **Boiling Heat Transfer in Small Horizontal Tube Bundles at Low Cross-Flow Velocities**, *International Journal of Heat and Mass Transfer*, 38(4):599-605, 1995 (7 pages, rdb9405)

heat transfer

A. A. Alhusseini, B. C. Hoke, and J. C. Chen, **Critical Heat Flux in Falling Films Undergoing Nucleate Boiling**, *Convective Flow Boiling* (proceedings of the Convective Heat Flow Boiling Conference, Banff, Canada, 30 April - 5 May 1995), Taylor and Francis, Limited, UK, 339-344, 1996 (6 pages, rdb8822)

measurements of critical heat flux on the outside of a vertical plain tube for R-113, R-718 (water), and an aqueous isopropanol mixture

Z. H. Ayub and S. K. Knewitz, **Limited Inventory Ammonia Falling-Film Spray Evaporator**, *Technical Papers of the 13th Annual Meeting* (March 1991, San Francisco, CA), International Institute of Ammonia Refrigeration (IIAR), Washington, DC, 61-78, 1991 (8 pages, rdb5728)

R-717, heat transfer

J. Bandel and E. U. Schlünder, **Pressure Drop and Heat Transfer by Vaporization of Boiling Refrigerants in a Horizontal Tube**, Hemisphere Publishing Corporation, Washington, DC, 365-387, 1986 (23 pages, rdb9406)

heat transfer

G. Barthau, **Active Nucleation Site Density and Pool Boiling Heat Transfer - An Experimental Study**, *International Journal of Heat and Mass Transfer*, 35(2):271-278, 1992 (8 pages, rdb3B35)

heat transfer

E. Berends and J. G. Romijn (Grenco Refrigeration B.V., The Netherlands), **The Influence of Oil Presence on the Performance of Ammonia Evaporators and Condensers**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 127-137, 1998 (11 pages with 5 figures and 1 table, RDB9208)

outlines laboratory and field tests of a naphthenic mineral oil (MO, Witco Suniso® 4GS) and a partially-synthetic lubricant (Mobil JHC) on heat exchange for R-717 (ammonia) systems; presents two models to calculate the influence of the lubricants on heat exchanger performance; describes an oil separator ("oil wash column") to return oil to the compressor; cites a 10-20% efficiency improvement in an ammonia system with eight screw compressors following addition of four oil separators; includes discussion by N. J. Hewitt (University of Ulster, UK), J. U. Marek (Novo Nordisk Engineering A/S, Denmark), R. A. Cole (R. A. Cole and Associates Incorporated, USA), M-J. Wing (Sunwell Engineering, Canada), and K. Stephan (Universität Stuttgart, Germany)

D. B. Bivens and A. Yokozeki (DuPont Chemicals), **Heat Transfer of Zeotropic Refrigerant Mixtures**, *Heat Pumps for Energy Efficiency and Environmental Progress* (proceedings of the Fourth International Energy Agency (IEA) Heat Pump Conference, Maastricht, The Netherlands, 26-29 April 1993), Elsevier Science Publishers B.V., Amsterdam, The Netherlands, 1993 (rdb7524)

heat and mass transfer, blends

T. W. Botsch, K. Stephan, J-L. Alcock, and D. R. Webb (Universität Stuttgart, Germany), **An Experimental Investigation of the Dynamic Behaviour of a Shell-and-Tube Condenser**, *International Journal of Heat and Mass Transfer*, 40(17):-4129-4135, 1997 (13 pages, rdb9917)

condensing heat transfer

T. W. Botsch, K. Stephan, J-L. Alcock, and D. R. Webb (Universität Stuttgart, Germany), **Modelling and Simulation of the Dynamic Behaviour of a Shell-and-Tube Condenser,** *International Journal of Heat and Mass Transfer*, 40(17):4137-4149, 1997 (13 pages, rdb9918)

condensing heat transfer

A. M. Bredesen (Norwegian University of Science and Technology, NTNU, Norway), A. Hafner (SINTEF Energy, Norway), J. Pettersen (SINTEF), P. Nekså (SINTEF), and K. Aflekt (NTNU), **Heat Transfer and Pressure Drop for In-Tube Evaporation of CO_2**, *Heat Transfer Issues in Natural Re-*

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frigerants (proceedings of the IIR Conference -meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 35-49, 1997 (15 pages with 30 figures, RDB9803)

describes apparatus and a test strategy to determine local heat transfer coefficients (HTCs) and pressure drops for R-744 (carbon dioxide) in small diameter (7 mm, 0.28"), aluminum tubes; compares measured data for neat refrigerants (without lubricants) to predictions; identifies research needs including further measurements, tests with lubricants present, and refinement of heat transfer correlations

S. T. Brekke, **Heat Transfer and Pressure Drop Gradient for Evaporating CO_2 Flow in Tubes**, master of science thesis, Norgest Tekniska Högskole (NTH), Trondheim, Norway, 1996 (in Norwegian, rdb9830)

heat transfer and pressure drop of R-744 (carbon dioxide)

E. Brendeng, **Influence of Internal Turbulators on Heat Transfer in Evaporator Tubes**, *Le Froid au Service de l'Homme* [Refrigeration for Service of Man] (proceedings of the XVlth International Congress of Refrigeration, Paris, France, 1983), International Institute of Refrigeration (IIR), Paris, France, 1:183-187, 1983 (5 pages, rdb9424)

heat transfer of R-12 inside a copper tube with an internal twisted strip

S. Caplanis, **Wärmeübergang und Blasenbildung an Hochleistungs-Verdampferrohren** [Heat Transfer and Nucleation in High Performance Evaporator Tubes], dissertation, Universität Paderborn, Germany, 1997 (rdb9860)

measurements of bubble formation in nucleate boiling, heat transfer, evaporator, heat exchanger

A. Cavallini, L. Doretti, M. Klammsteiner, G. A. Longo, and L. Rosetto (Università di Padova, Italy), **Condensation of New Refrigerants Inside Smooth and Enhanced Tubes**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:105-114, 1995 (10 pages with 4 figures and 4 tables, rdb7731)

procedures for computing the transfer during condensation of R-32, R-124, R-125, R-134a, R-152a, and blends of them in plain and microfin tubes; comparison of published models; proposal for a new model

J. Chen, Q. Wang, K. Tuzla (Lehigh University), and K. E. Starner (York International Corporation), **Falling Film Evaporation of Refrigerants**, *Heat Transfer 1994* (proceedings of the Tenth International Heat Transfer Conference, Brighton, UK), Institution of Chemical Engineers (IChemE), Rugby, UK, 6:169-173, 1994 (5 pages, rdb8520)

heat transfer

M. C. Chyu, X. Zeng (Texas Tech University), and Z. H. Ayub (ThermalFluid International), **Nozzle-Sprayed Flow Rate Distribution on a Horizontal Tube Bundle**, paper 3919 (725-RP), *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):443-453, 1995 (11 pages with 11 figures, RDB8521)

analysis of spray flow rates from nozzles reaching horizontal tubes at different locations in a tube bundle: flow rates are predicted based on given total nozzle flow rate nozzle height, nozzle interval, spray angle, tube diameter, and the horizontal distance between the tube and the nozzles; both round and square full-cone nozzles are addressed; results are compared to measured data

J. G. Collier and J. R. Thome, **Convective Boiling and Condensation** (third edition), Oxford University Press, Oxford, UK, 1994 and 1996 (rdb5246)

survey of two-phase flow and heat transfer

G. Costigan, D. P. Frankum, and V. V. Wadekar, **Flow Boiling Measurements on Pentane, Iso-Octane, and Pentane/Iso-Octane Mixtures**, *Heat Transfer 1994* (proceedings of the Tenth International Heat Transfer Conference, Brighton, UK), Institution of Chemical Engineers (IChemE), Rugby, UK, 7:431-436, 1994 (6 pages, rdb9407)

heat transfer and flow boiling; R-601, R-604a (isooctane), R-601 /604a

G. N. Danilova, V. M. Azarskov, B. B. Zemskov, A. A. Malyshev, and V. K. Kirin, **Heat Transfer and Two-Phase Flow of Freons in Evaporators of Refrigerators,** *Heat Transfer - Soviet Research*, 18(6):18-23, 1984 (6 pages, RDB9408)

heat transfer and fluid flow

J. Darabi, M. Salehi, M. H. Saeedi (Sharif University of Technology, Iran), and M. M. Ohadi (University of Maryland), **Review of Available Correlations for Prediction of Flow Boiling Heat Transfer in Smooth and Augmented Tubes,** paper CH-95-12-*2, Transactions* (Winter Meeting, Chicago, IL, 28 January - 1 February 1995), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(1):965-975, 1995 (11 pages with 2 figures and 4 tables, RDB5234)

heat transfer

H-J. de Buhr and S. Kabelac (Universität Hannover, Germany), **Flow Boiling Heat Transfer of Ammonia and Ammonia-Oil Mixtures**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 138-145, 1998 (8 pages with 7 figures, RDB9209)

study of flow boiling of R-717 (ammonia); addresses prediction of the heat transfer coefficient (HTC); discusses problems with use of maps of flow patterns and correlations of pressure drop in nonadiabatic situations; also discusses the influence of constant heat flux as a boundary condition; describes planned tests of low boiling in horizontal plain and enhanced tubes, using capacitive tomography to detect flow patterns, for the Arbeitsgemeinschaft industrieller Forschungsvereinigungen (AIF) [Partnership for Industrial Research Activities]

H-J. de Buhr and S. Kabelac, **AIF Forschungsvorhaben 'Aluminium als Werkstoff für Ammoniak-Kälteanlagen'. Literaturrecherche zum Thema Strömungssieden (Anhang zum Zwischenbericht 1996)** [AIF Research Project "Aluminum as a Material for Ammonia Refrigeration". Literature Search on the Subject of Flow Boiling (Supplement to Interim Report 1996)], Institut für Thermodynamik, Universität Hannover, Germany, 1997 (in German, rdb9210)

literature search on flow boiling of R-717 (ammonia) conducted for the Arbefsgemeinschaft industrieller Forschungsvereinigungen (AIF) [Partnership for Industrial Research Activities]

V. K. Dhir, **Nucleate and Transition Boiling Heat Transfer Under Pool and External Flow Conditions**, *Heat Transfer 1990* (proceedings of the Ninth International Heat Transfer Conference, Jerusalem, Israel), Hemisphere Publishing Corporation, New York, NY, 1:129-155, 1990 (27 pages, rdb9855)

heat transfer, evaporation, heat exchangers

Y. Ding, S. Kacac, and X. J. Chen, **Stratification of Boiling Two-Phase Flow in a Single Horizontal Channel**, *Heat and Mass Transfer*, 30(3):187-195, 1995 (9 pages, rdb9409)

R-11 heat transfer and fluid flow in a smooth steel channel for 2-24 °C (36-75 °F)

H. Ettle and K. Stephan (Universität Stuttgart, Germany), **Influence of Critical Phenomena on the Heat Transfer to Binary Mixtures**, *International Journal of Heat and Mass Transfer*, 34(1):209-216, 1990 (8 pages, rdb9922)

heat transfer for blends

I. Golobic and B. Gaspersic (University of Ljubljana, Slovenia), **Prediction of Pool Boiling Heat Transfer with New Refrigerants Based on Thermodynamic Similarity**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:230-237, 1995 (8 pages with 5 figures and 1 table, rdb7809)

nucleate pool boiling heat transfer coefficients on plain tubes: review of published methods by Stephan and Abdelsalam, Westwater, Cooper, Danilova, Gorenflo, Bier and Lambert, and Leiner; proposed method based on heat flux, the thermophysical properties of the fluid, properties of the heating surface, and surface geometry

D. Gorenflo, A. Luke, G. Herres, R. Köster, P. Kaupmann, P. Hübner, K. Möller, and E. Danger (Universität Paderborn, Germany), **Wärmeübergang beim Sieden in überfluteten Verdampfern: Neue Ergebnisse und Stand der Berechnungsmethoden** [Boiling Heat Transfer in Overfed Evaporators: New Results and Status of Calculation Methods], *Bericht über die Kälte-Klima-Tagung* [Proceedings of the Refrigeration and Air-Conditioning Conference], Deutscher Kälte- and Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, 25(II.I):, 1998 (rdb9864)

calculation methods for boiling heat transfer, evaporation, heat exchangers

D. Gorenflo, A. Luke, and E. Danger (Universität Paderborn, Germany), **Interactions between Heat Transfer and Bubble Formation in Nucleate Boiling**, *Heat Transfer 1998* (proceedings of the 11th International Heat Transfer Conference, Kyongju), Taylor and Francis Publishers, Levittown, 1:149-174, 1998 (26 pages, rdb9857)

heat transfer, evaporation, heat exchangers

D. Gorenflo (Universität Paderborn, Germany), **Behältersieden (Sieden bet freier Konvektion)** [Pool Boiling (Boiling by Free Convection)], *VDI-Wärmeatlas* [Thermal Atlas of the Association of German Engineers] (eighth edition), Springer Verlag, Berlin, Germany, 1997 (rdb9863)

prediction methods for pool boiling heat transfer

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U. Groß (Universität Stuttgart, Germany), **Einfluß von Öl auf die Zwangskonvektion im Verdampferrohr** [Influence of Oil on Forced Convection in Evaporator Tubes], *DKV Jahrestagung* [Proceedings of the DKV Annual Meeting] (Nürnberg, 1993), Deutscher Kälte- and Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, 1993 (in German, rdb9417)

heat transfer

S. Ha (Goldstar Company Limited, Korea) and A. E. Bergles (Rensselaer Polytechnic Institute, RPI), **Some Aspects of Experimental In-Tube Evaporation**, publication unknown, 187-192, 1993 (6 pages, rdb9426)

heat transfer for R-12 with 0-5% lubricant inside smooth and microfin copper tubes

A. Hafner, **Design and Development of CO_2 Heat Exchangers**, *Compression Systems with Natural Working Fluids* (proceedings of the IEA HPC Annex 22 Workshop, Gatlinburg, TN, 2-3 October 1997), International Energy Agency (IEA) Heat Pump Centre (HPC), Sittard, The Netherlands, 1997 (rdb-8818)

measurement of local heat transfer for R-744 in smooth tubes at -10 °C (14 °F)

K. Hambraeus (Kungliga Tekniska Högskolan, KTH, Sweden), **Two Phase Flow Boiling of an Oil-HFC-134a Mixture**, paper 91, *New Challenges in Refrigeration* (proceedings of the XVIIIth International Congress of Refrigeration, Montreal, Québec, Canada, 10-17 August 1991), International Institute of Refrigeration, Paris, France, 11:499-503, August 1991 (5 pages with 4 figures and 2 tables, RDB4938)

heat transfer coefficients for two-phase boiling R-134a/lubricant mixtures; the tested lubricants are experimental oils (CPI 0275 and 0323)

K. Hashimoto and M. Saikawa (Central Research Institute of Electric Power Industry, CRIEPI, Japan), **Preliminary Experimental Results of CO_2 Gas-Cooling Overall Heat Transfer Coefficient Under Supercritical Condition**, *Heat Transfer Issues In Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 50-58, 1997 (9 pages with 12 figures and 3 tables, RDB-9804)

describes a test rig and summarizes preliminary measurements of overall heat transfer coefficients (HTCs) of R-744 (carbon dioxide) at supercritical gas cooling conditions in copper tubes

G. F. Hewitt, **Phenomenological Issues in Forced Convective Boiling**, *Convective Flow Boiling* (proceedings of the Convective Heat Flow Boiling Conference, Banff, Canada, 30 April - 5 May 1995), Taylor and Francis, Limited, UK, 3-14, 1996 (12 pages, rdb8A10)

droplet entrainment and deposition in the annular flow regime: presents simulations for annular flow that model the turbulence and temperature fields formed at the interface of annular films; addresses the shortcomings of current models for forced convective boiling inside plain tubes

G. F. Hewitt and D. G. Owen, **Pressure Drop and Entrained Fraction in Fully Developed Flow**, 145-154, 1985 (10 pages, rdb9410)

heat transfer and fluid flow

K. Hijata, **Forced Convective Condensation of a Nonazeotropic Binary Mixture on Vertical and Horizontal Tubes**, *Heat Transfer 1990* (proceedings of the Ninth International Heat Transfer Conference, Jerusalem, Israel), Hemisphere Publishing Corporation, New York, NY, 3:271-276, 1990 (6 pages, rdb6705)

zeotropic blends, heat transfer

E. Hofmann (Linde Aktiengesellschaft, Germany), **Efficiency of Dry Expansion Evaporators with Bare and Inside Finned Tubes**, publication unknown, 305-318, 1993 (14 pages, rdb9427)

heat transfer

H. J. Hogaard-Knudsen and P. H. Jensen, **Heat Transfer Coefficient for Boiling Carbon Dioxide**, *Compression Systems with Natural Working Fluids* (proceedings of the IEA HPC Annex 22 Workshop, Gatlinburg, TN, 2-3 October 1997), International Energy Agency (IEA) Heat Pump Centre (HPC), Sittard, The Netherlands, 1997 (rdb8819)

measurement of local heat transfer for R-744 in smooth tubes at -25 and -10 °C (-13 and 14 °F)

E. C. Hong, M. S. Kim, and S. T. Ro (Seoul National University, Korea), **Prediction of Evaporative Heat Transfer Coefficient of Pure Refrigerants and Binary Refrigerant Mixtures in a Horizontal Tube,** *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:313-320, 1995 (8 pages with 9 figures, rdb7820)

correlation to predict heat transfer coefficients (HTCs) for binary zeotropes with validation for R-22/12 and R-22/114, binary zeotropes

M. K. Huen, **Performance and Optimization of Microchannel Condensers**, PhD thesis (Department of Mechanical Engineering), University of Illinois at Urbana-Champaign, 1995 (rdb8518)

Gnielinski relation for heat transfer in microchannel heat exchangers

Y. H. Hwang, B. H. Kim, and R. K. Radermacher (University of Maryland), **Boiling Heat Transfer Correlation for Carbon Dioxide**, *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 81-95, 1997 (15 pages with 20 figures and 2 tables, RDB-9807)

compares measured data by Bredesen to the Chen, Bennett-Chen, Güngör-Winterton (identified in the paper as "Gungor-Winston"), Shah, Schrock-Grossman, and Liu-Winterton correlations to model boiling heat transfer of R-744 (carbon dioxide); indicates that they are not suitable except for the Bennett-Chen correlation; proposes a modified Bennett-Chen correlation, but indicates that additional measured data are needed to insure accuracy

Y. H. Hwang and R. K. Radermacher (University of Maryland), **Evaluation of Carbon Dioxide Heat Exchanger**, *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 106-115, 1997 (10 pages with 9 figures and 2 tables, RDB9809)

summarizes theoretical and experimental investigations of heat exchangers for R-744 (carbon dioxide); compares measured data to models identified as EVAPRO for the evaporator and GASPRO for the gas cooler to simulate a transcritical cycle; investigates the effects of chilled water and cooling water temperatures on performance

M. Inagaki, H. Sasaya, and Y. Ozakli (Nippon Soken Incorporated, Denso Corporation, Japan), **Pointing to the Future: Two-Stage CO_2 Compression**, *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 131-138, 1997 (8 pages with 14 presentation charts and summary, RDB9812)

describes a two-stage compression cycle for R-744 (carbon dioxide) using a swash-plate compressor; indicates 15 and 7% improvements in efficiency and capacity, respectively, compared to a single-stage approach; presents a mechanical expansion valve that maintains an optimal high-side pressure

Institut für Thermodynamik und Wärmetechnik (ITW) [institute for Thermodynamics and Thermal Technology] (Universität Stuttgart, Germany), **Wärmeübergang beim Sieden der Gemische R404A, R507, R407C, und R410A** [Boiling Heat Transfer of the Mixtures R-404A, R-507A, R-407C, and R-410A], Forschungsrat Kältetechnik [Refrigeration Research Council], Frankfurt am main, Germany, October 1995 (in German, rdb8C08)

heat transfer of blends

M. K. Jensen and B. Shome (Rensselaer Polytechnic Institute, RPI), **Literature Survey of Heat Transfer Enhancement Techniques in Refrigeration Applications**, report ORNL/Sub/91-SL794, Oak Ridge National Laboratory, Oak Ridge, TN, May 1994 (394 pages with 77 figures, available from JMC as RDB4892)

D. Jung, C. B. Kim, K. H. Song, and J. K. Lee (Inha University, Korea), **Pool Boiling Heat Transfer Coefficients of Propane, Butane, and their Mixtures,** *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 221-230, 1997 (10 pages with 6 figures and 1 table, RDB9821)

presents measurements of heat transfer coefficients (HTCs) for R-22, R-134a, R-290 (propane), R-600a (isobutane), R-290/600a (25/75), R-290/600a (50/50), and R-290/600a (75/25) in a 19 mm (3/4"), plain copper tube at 4 °C (39 °F): results show the HTCs for R-290 to be 15% higher than for R-22 while those of R-134a and R-600a are 15 and 33% lower, respectively; the HTCs for the blends are up to 35% lower than predictions by a simple ideal mixing rule; also indicates that the correlation by Stephan and Abdelsalam (see RDB4424) underpredicts the HTCs of neat hydrocarbons [note that the paper makes multiple references to R-600a and to isobutane even though the title suggests the focus to be on R-600 (n-butane)]

D. Jung (Inha University, Korea) and R. K. Radermacher (University of Maryland), **Prediction of Evaporation Heat Transfer Coefficient and Pressure Drop of Refrigerant Mixtures,** *International Journal of Refrigeration* (IJR), 16(5):330-338, June 1993 (9 pages with 6 figures and 5 tables, RDB4420)

This article presents a study of the heat transfer coefficient (HTC) and pressure drop of refrigerant mixtures. Predicted HTCs and pressure drops are reported for blends under consideration as R-12 and R-22 alternatives. The article reviews heat transfer correlations with measured data, and conceptually illustrates the dependence of HTC on heat flux and quality in the nucleate boiling regime, and on quality in the convective evaporation regime. The results indicate that nucleate boiling is suppressed at qualities greater than 20% for all mixtures, and evaporation becomes the main heat transfer mechanism. The article then reviews the pressure drop correlation used and discusses alternative comparisons for mixtures to pure fluids. It concludes that equivalent cooling capacity offers a more meaningful basis than equivalent mass flow rates. Differences in respective volatilities of the mixture components are discussed. Predicted HTC values are tabulated for R-12, R-22, R-32, R-123, R-141b, R-142b, and R-152a and given as ratios to the HTC of R-12 over a quality range of 20-90% at evaporator temperatures of -10, 0, and 10 °C (14, 32, and 50 °F). Similar data are presented for R-12 alternatives including R-22/123 (60/40), R-22/141b (70/30), R-22/142b (50/50), R-22/152a (20/80), R-32/141b (20/80), and R-32/152a (10/90) and for R-22 substitutes, R-32/142b (50/50) and R-32/152a (40/60). Predicted pressure drops are plotted for the same fluids. A table compares the overall HTC for mixtures of R-22/123 (60/40) and R-12 in air and water systems. A figure illustrates the predicted pressure drop of the cited blends and of R-12 and R-22 at -10, 0, and 10 °C (14, 32, and 50 °F). The paper notes that HTC values are sensitive to liquid viscosity and thermal conductivity; 10% uncertainty in them results in a 6% change in HTC. The paper concludes that nucleate boiling is fully suppressed for pure and mixed refrigerants and that HTC increases monotonically with quality in the evaporating range discussed. Further, while some mixtures exhibit as much as 90% higher HTC than R-12 and R-22 at uniform mass flow rates, mixtures containing R-32 and R-152a show only 8-10% increase for the same cooling capacity because of reduced mass flow rates. Mixtures of components with large volatility differences show up to 55% HTC reduction. The significance depends on the heat transfer fluid; the overall reduction is less than 1.5% in air-to-refrigerant heat exchangers, but as much as 20% in water-to-refrigerant exchangers. The pressure drops of all the mixtures examined are smaller due to the lower mass flows.

M. A. Kedzierski, **Effect of Inclination on the Performance of a Compact Brazed Plate Condenser and Evaporator**, report NISTIR 5767, National Institute of Standards and Technology (NIST), Gaithersburg, MD, November 1995 (38 pages with 10 figures and 6 tables, available from NTIS, RDB6433)

This report summarizes tests to measure performance changes associated with tilting a compact brazed plate heat exchanger (CBE) from a vertical orientation. It summarizes tests, using R-22 in a CBE (SWEP B15x36) rotated in clockwise and counterclockwise directions, to assess the influence of gravity. The report recaps published studies of performance and growing use of CBEs in refrigeration. It describes and schematically illustrates the test apparatus used, outlines the analysis methods, and presents the findings. The study found a substantial performance penalty when the evaporator was rotated past 30° from the vertical. The capacity in the horizontal position was 62-74% of the vertical value. For a rotation angle of 30°, the degradation performance was within 5% of the vertical value. Rotation direction and entering refrigeration state had little effect on performance for rotation less than 60°. Only when the evaporator was rotated to the horizontal position did rotation direction and refrigerant state have much effect. At the horizontal position, a subcooled entering refrigerant and a counterclockwise rotation both tended to lessen the capacity degradation. Rotation of the CBE condenser to the horizontal position improve the overall heat transfer coefficient by approximately 25%. Rotation direction had a negligible effect on the performance of the condenser. No mention is made of lubricant presence or interactions for these tests.

M. A. Kedzierski and M. P. Kaul, **Horizontal Nucleate Flow Boiling Heat Transfer Coefficient Measurements and Visual Observations for R12, R134a, and R134a/Ester Lubricant Mixtures,** report NISTIR 5144, National Institute of Standards and Technology (NIST), Gaithersburg, MD, March 1993 (36 pages with 10 figures and 1 table, available from NTIS, RDB3419)

This report presents a calorimetric and visual investigation of nucleate flow boiling of R-12 and R-134a inside horizontal tubes. Mixtures of R-134a with 0.9% polyolester lubricant (Castrol Icematic® SW100) and 0.9 and 2.3% neopentyl polyolester (ICI Emkarate™ 213b, a developmental lubricant) also were investigated. The report documents both calorimetric measurements of the local two-phase heat transfer coefficients and simultaneous visual measurements, using high-speed photography. Derived bubble diameters and densities are presented. The test apparatus, instrumentation procedures, and calorimetric and visual results are described. Plots are provided of the heat transfer coefficient measurements for a range of heat fluxes for Reynolds numbers of zero to approaching 10,000. Good agreement was achieved with the Borishanskii-Minchenko equation. For both R-12 and R-134a, an increase in either the heat flux or Reynolds number of the flow increases the heat transfer coefficient, though the former has a larger effect. Visual observations of the bubble density and size are used to explain the heat transfer trends. Faster bubble formation by R-134a correlated with superior heat transfer. The authors offer a probable explanation for observed heat transfer enhancement of neopentyl polyolester mixture over pure R-134a. They attribute it to canceling effects of drastic reduction in bubble diameters and significant increase in site density. Boiling appeared to occur from lubricant-rich clouds, acting like porous surfaces, on the heater portion of the tube.

M. A. Kedzierski, J. H. Kim, and D. A. Didion (National Institute of Standards and Technology, NIST), **Causes of the Apparent Heat Transfer Degradation for Refrigerant Mixtures**, *Two-Phase Flow and Heat Transfer* (proceedings of the 28th National Heat Transfer Conference, San Diego, CA, 9-12 August 1992), American Society of Mechanical Engineers (ASME), New York, NY, HTD-197:149-158, 1992 (10 pages, rdb3B22)

M. A. Kedzierski and D. A. Didion (National Institute of Standards and Technology, NIST), **A Comparison of Experimental Measurements of Local Flow Boiling Heat Transfer Coefficients for R-11 and R-123**, *Proceedings of the Third ASME/JSME Thermal Engineering Joint Conference* (Reno, NV, 17-22 March 1991), American Society of Mechanical Engineers (ASME), New York, NY, Japan Society of Mechanical Engineers (JSME), Tokyo, Japan, 3:243-250, 1991 (8 pages, rdb3B23)

S. N. Kondepudi (Electric Power Research Institute, EPRI), **Heat Transfer Testing of Alternate Refrigerants to R-22**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:361-365, 1995 (5 pages with 1 table, rdb7825)

experimental methods and key findings for three studies of heat transfer for the Alternative Refrigerants Evaluation Program (AREP): R-32/125 (60/40) offered the best performance of the R-22 alternatives followed by R-134a, but both dropped with the presence of lubricants

V. Knabe, **Züm Einfluß der Heizflächenrauhigkeit auf den Wärmeübergang und die maximale Wärmestromdichte beim Blasensieden** [On the Influence of Surface Finish on Heat Transfer and the Maximum Heat Flux Density in Nucleate Boiling], dissertation, Universität Paderborn, Germany, 1984 (rdb9870)

influence of surface roughness on bubble formation in nucleate boiling, heat transfer, evaporator, heat exchanger

B. A. Krueger, B. D. Krueger, T. A. Newell, and J. C. Chato (University of Illinois at Urbana-Champaign), **A Literature Survey of Alternative Refrigerants During Single-Phase Heat Transfer**, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, December 1998 (32 pages with 1 table, available from JMC as RDB9305)

review of single-phase flow data as well as heat transfer and thermophysical properties based on a literature review and assessment; also addresses lubricant effects on heat transfer and heat transfer enhancement; emphasis is on R-22, R-134a, R-404A, R-407C, R-502, and R-507A; cites 77 references and concludes that "essentially no information is available in peer-reviewed journal publications on single-phase flow for newer refrigerants"; also concludes that common correlations for single-phase flow are applicable, but that there is high uncertainty in the range of laminar flow with high Reynolds numbers through turbulent flow with low Reynolds numbers due to a lack of experimental data; recommends research to fill the voids with focus on microchannel and microfin heat exchangers

W. Leiner, **Heat Transfer by Nucleate Pool Boiling - General Correlation Based on Thermodynamic Similarity**, *International Journal of Heat and Mass Transfer*, 37:763-769, 1994 (7 pages, rdb9866)

prediction of boiling heat transfer, evaporation

J. H. Lienhard, **Snares of Pool Boiling Research: Putting Our History to Use**, *Heat Transfer 1994* (proceedings of the Tenth International Heat Transfer Conference, Brighton, UK), Institution of Chemical Engineers (IChemE), Rugby, UK, 1:333-348, 1994 (16 pages, rdb9856)

heat transfer, evaporation, heat exchangers

A. Luke and D. Gorenflo (Universität Paderborn, Germany), **Nucleate Boiling Heat Transfer of HFCs and HCs in Heat Pumps Application: State of the Art and New Developments,** *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May -2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 15, 1999 (10 pages with 6 figures, RDB9854)

reviews the status and recent developments in nucleate boiling heat transfer in evaporators; observes-that historic methods relied on empirical approaches, but new methods may enable prediction with quantitative information on surface roughness and fluid characteristics; discusses nucleate boiling of hydrocarbon (HC) and hydrofluorocarbon (HFC) refrigerants, both as single compounds and as blends, on tubes

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of copper and steel with different surface finishes (for example smooth, ground, and sandblasted); presents measured data on the influences of thermophysical properties and surface roughness; proposes a relation between surface structure and bubble formation in surface cavities; identifies research needs to improve the relation

A. Luke (Universität Paderborn, Germany), **Pool Boiling Heat Transfer from Different Tubes with Different Surface Roughness**, *International Journal of Refrigeration* (IJR), 20(8):561-574, December 1997 (14 pages with 18 figures and 1 table, RDB-9868)

heat transfer of R-290 (propane) on copper and steel tubes with different finishes, effects of surface structure on nucleation

A. Luke, **Beitrag zum Einfluß der Mikrostruktur von Heizflächen auf den Wärmeübergang beim Blasensieden** [Contribution on the Influence of Microstructure of Hot Surfaces on Heat Transfer in Nucleate Boiling], dissertation, Universität Paderborn, Germany, 1996 (rdb9861)

measurements of bubble formation in nucleate boiling, surface enhancement, heat transfer, evaporator, heat exchanger

P. G. Lundqvist (Kungliga Tekniska Högskolan, KTH, Sweden), **Analysis of Plate Type Heat Exchangers with Zeotropic Refrigerant Blends**, proceedings (Winter Annual Meeting, San Francisco, CA), American Society of Mechanical Engineers (ASME), New York, NY, AES-34:37-58, 1995 (22 pages, rdb4759)

B. B. Mikic and W. M. Rosenhow, **A New Correlation of Pool Boiling Data Including the Effect of Heated Surface Characteristics**, *Journal of Heat Transfer*, 91:245-250, 1969 (6 pages, rdb9858)

analysis of heat transfer

C. Möller, U. Groß, and E. Hahne (Universität Stuttgart, Germany), **Einfluß von Öl auf den Wärmeübergang beim Sieden von R134a** [Influence of Oil on Boiling Heat Transfer for R-134a], Conference Report Number 18, Deutscher Kälte- und Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, 93-108, 1991 (16 pages with 14 figures, in German, rdb4221)

This paper summarizes a study of the heat transfer of mixtures of R-134a with a polyolester lubricant (ICI Emkarate™) using an electrically-heated platinum wire. The dependence of the heat transfer coefficient on the heat flux density was measured for temperatures varying between -16 and 32 °C (3 and 90 °F) and lubricant concentration from 0 to 15% by mass. The results are compared to those for R-12 with a mineral oil (Shell Clavus 129).

C. Möller, K. Shi, U. Groß, and E. Hahne (Universität Stuttgart, Germany), **Einfluß von Öl auf den Wärmeübergang beim Sieden von neuer Kältemittel** [Influence of Oil on Boiling Heat Transfer for New Refrigerants], *DKV-Statusbericht* [Status Report] 6, Deutscher Kälte- and Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, 73-76, 1990 (4 pages in German, rdb4937)

K. Moser, R. L. Webb, and B. Na (Pennsylvania State University), **A New Equivalent Reynolds Number Model for Condensation in Smooth Tubes**, *Journal of Heat Transfer*, circa 1997 (rdb-9826)

analysis of heat transfer

P. Nekså H. Rekstad, and G. R. Zakeri (Norwegian University of Science and Technology, NTNU, Norway), **CO_2 Prototype Hot Water Heat Pump Characteristics, System Design and Experimental Results,** *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 165-172, 1997 (8 pages with 8 figures, RDB9332)

describes a prototype, experimental results, and design features for a 50 kW (170 Mbh) water-to-water heat pump using R-744 (carbon dioxide) in a transcritical cycle; indicates a measured heating coefficient of performance (COP) of 3.6-4.3 for evaporator temperatures of -10 to 0 °C (14 to 32 °F) and a delivered hot water temperature of 60 °C (140 °F) with an assumed motor efficiency of 90%

M. Niederkrüger, **Strömungssieden von reinen Stoffen und binären zeotropen Gemischen im waagerechten Rohr milt mittleren und hohen Drücken: Wärmeübergang, Druckverlust, Strömungsformen, dargestellt für das Stoffsystem Schwefelhexafluorid-Dichlordifluormethan** [Flow Boiling of Pure Substances and Binary Zeotropic Mixtures in Enhanced Tubes at Intermediate and Higher Pressures: Heat Transfer, Pressure Drop, Flow Profile, Represented by the System of Sulfur Hexafluoride with Dichlorodifluoromethane], *Fortschritt-Berichte VDI,* VDI-Verlag, Düsseldorf, Germany, 3(245), 1991 (in German, rdb9412)

heat transfer, R-7146/12

M. M. Ohadi, S. S. Li, R. K. Radermacher, and S. V. Dessiatoun (University of Maryland), **Critical Review of Available Correlations for Two-Phase**

Flow Heat Transfer of Ammonia, *International Journal of Refrigeration* (IJR), 19(4):272-284, May 1996 (13 pages with 5 figures, RDB9811)

critical review of the published literature on heat transfer of R-717 (ammonia): identifies sources of thermal property data; evaluates available correlations for boiling and evaporation inside and outside tubes with attention to local heat transfer in plain tubes, heat transfer coefficients (HTC) for flow boiling in plain tubes, flow boiling in a plate-fin heat exchanger, falling film evaporation over horizontal tubes, pool boiling correlations, enhancement, effects of pressure and water contamination, and evaporation in free-falling droplets; similarly evaluates predictive methods for condensation including film condensation on horizontal and vertical smooth tubes, enhancement, influences of tube orientation, use of fluted tubes and finned surfaces, and condensation on coiled-fluted tubes; identifies research needs

M. M. Ohadi, S. Dessiatoun, A. Singh, and M. A. Fanni (University of Maryland), **EHD Enhancement of Pool and In-Tube Boiling of Alternative Refrigerants**, final report DOE/CE/23810-17, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, August 1993 (62 pages with 13 figures, available from JMC as RDB3A16)

M. M. Ohadi, R. A. Papar, A. Kumar, and A. I. Ansari (University of Maryland), **Some Observations on EHD-Enhanced Boiling of R-123 in the Presence of Oil Contamination**, *Pool and External Flow Boiling* (proceedings of the Engineering Foundation Conference Pool and External Flow Boiling, Santa Barbara, CA, 22-27 March 1992), edited by V. K. Dhir and A. E. Bergles, American Society of Mechanical Engineers (ASME), New York, NY, 387-396, 1992 (10 pages with 26 figures and 1 table, RDB3C16)

M. M. Ohadi, R. A. Papar, T. L. Ng, M. A. Faani, and R. K. Radermacher (University of Maryland), **EHD Enhancement of Shell-Side Boiling Heat Transfer Coefficients of R-123/Oil Mixture,** paper BA-92-5-1, *Transactions* (Annual Meeting, Baltimore, MD, June 1992), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 98(2):427-434, 1992 (8 pages with 10 figures and 1 table, RDB2608)

C. Pais and R. L. Webb (Pennsylvania State University), **Literature Survey of Pool Boiling on Enhanced Surfaces**, technical paper 3444 (392-RP), *Transactions* (Winter Meeting, New York, NY, 19-23 January 1991), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 97(1):79-89, 1991 (11 pages, rdb2405)

heat exchangers, heat transfer

R. A. Papar, M. M. Ohadi, A. Kumar, and A. I. Ansari (University of Maryland), **Effect of Electrode Geometry on EHD-Enhanced Boiling of R-123/Oil Mixture,** paper CH-93-14-4, *Transactions* (Winter Meeting, Chicago, IL, January 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(1):1237-1243, 1993 (11 pages with 5 figures, RDB3112)

J. C. Passos and D. Gentile, **An Experimental Investigation of the Transition Boiling in a Subcooled Freon 113 Forced Flow**, *Proceedings of the Symposium on Fundamentals of Gas-Liquid Flows* (ASME Winter Annual Meeting, Chicago, IL, 1988), publication FED-72, American Society of Mechanical Engineers (ASME), New York, NY, 57-61, 1988 (5 pages, rdb9413)

heat transfer, R-113

M. B. Pate (Iowa State University of Science and Technology), **Evaporation and Condensation Heat Transfer Coefficients for HCFC-124/HCFC-22/HFC-152a**, *Proceedings of the 1990 USNC/IIR-Purdue Refrigeration Conference and ASHRAE-Purdue CFC Conference,* edited by D. R. Tree, Purdue University, West Lafayette, IN, July 1990 (RDB2240)

heat transfer, R-22/152a/124, R-401 series zeotropic blend refrigerants

O. Pelletier and B. E. Palm (Kungliga Tekniska Högskolan, KTH, Sweden), **Boiling of Hydrocarbons in Small Plate Heat Exchangers**, *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 231-241, 1997 (11 pages with 11 figures and 1 table, RDB9822)

presents measurements of overall heat transfer coefficients (HTCs) for R-22, R-290 (propane), R-1270 (propene), Care 40 (nominally R-290), and Care 50 nominally an undisclosed blend of R-170/290); results show the HTCs for the hydrocarbons were up to 25% higher than for R-22 while the pressure drops were 25-40% lower

A. D. Pinto, **Wärmeübergang and Blasenbildung beim Sieden von Propan an einem geschmirgelten Kupferrohr in einem großen Druckbereich** [Heat Transfer and Boiling Nucleation of Propane on an Emery Ground Copper Tube in a Wide Range of Pressures], dissertation, Universität Paderborn, Germany, 1995 (rdb9862)

measurements of heat transfer and bubble formation in nucleate boiling of R-290 (propane) in

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surface-roughened copper tubes; evaporator, heat exchanger

R. Rieberer and H. Halozan (Technische Universität Graz, Graz, Austria), **Design of Heat Exchangers for CO_2 - Heat Pump Water Heaters**, *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 96-104, 1997 (9 pages with 12 figures, RDB9808)

summarizes laboratory tests to verify simulation and optimization methods for a heat pump water heater (HPWH) with R-744 (carbon dioxide) as the refrigerant in a transcritical cycle; test unit was designed to deliver 20 Kw (68,000 Btu/hr) with counter-flow heat exchangers; examines the influence of tube diameter and mass velocity on the two-phase heat transfer coefficients (HTCs) with attention to predicted dryout at low vapor quality

R. Rieberer and H. Halozan (Technische Universität Graz, Graz, Austria), **CO_2 Air Heating System for Low-Heating-Energy Buildings**, *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 156-164, 1997 (9 pages with 9 figures and 1 table, RDB9331)

discusses thermal load profiles of buildings to characterize those with low transmission relative to ventilation losses; discusses potential use of R-744 (carbon dioxide) as the refrigerant in a transcritical cycle; summarizes simulation results suggesting high efficiency; summarizes component development for a system test

D. M. Robinson and E. A. Groll (Purdue University), **Theoretical Analysis of Two-Phase Carbon Dioxide Heat Absorption Process,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 157-167, 1998 (11 pages with 5 figures and 2 tables, RDB9211)

summarizes modeling of the comparative heat transfer of R-22 and R-744 (carbon dioxide) in evaporation: heat exchangers are modeled as single, straight, plain tubes with outside fins of uniform thickness and spacing; the tube diameters and lengths for each refrigerant were based on the individual pressures and allowable pressure drop for the two refrigerants; presents the heat transfer models and plots of the results, concludes that the R-744 heat exchanger will be 29-40% shorter, weigh up to 27% less, and have a 29-40% smaller volume than the one for R-22

D. M. Robinson and E. A. Groll (Purdue University), **Theoretical Analysis of Supercritical Two-Phase Carbon Dioxide Heat Rejection Process,** *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 59-71, 1997 (13 pages with 6 figures and 2 tables, RDB9805)

compares heat exchanger models for the heat rejection processes (condensing and supercritical gas cooling, respectively) of R-22 and R-744 (carbon dioxide) for straight tubes with exterior fins of constant thickness and uniform spacing; compares the required lengths, weights, and internal volumes for the two refrigerants for an automotive air conditioner

J. Rogstam (Kungliga Tekniska Högskolan, KTH, Sweden), **Comparative Evaluation of Heat Transfer and Pressure Drop Characteristics of Cyciopropane, R600a, and R12**, *Heat Transfer Issues in Natural Refrigerants* proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 242-250, 1997 (9 pages with 13 figures, RDB9823)

presents measurements of pressure drop and overall heat transfer coefficients (HTCs) for R-C270 (cyclopropane) and R-600a (isobutane) normalized to those for R-12; concludes that the low liquid density of R-C270 will allow smaller refrigerant charges and yield lower pressure drop than with R-12 or R-600a; although not expected, the condensation heat transfer of R-C270 and R-600a were found to be similar to that for R-12; suggests that R-C270 could yield lower system costs

L. Rohlin, A. Win, K. V. Ravikumar, A. Vadas, K. Le, K. Huang, M. Hsieh, G. K. Peng, D. Law, and T. H. K. Frederking (University of California - Los Angeles, UCLA), **Heat Transfer Phenomena During Oscillations in an "Air Conditioning Pulse Tube": Selected Thermal Equilibrium Components and Phenomena**, *Heat Transfer Issues In Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 270-286, 1997 (17 pages with 12 figures, RDB9825)

analyses of heat transfer in thermoacoustic refrigeration systems (identified as Air Conditioning Pulse Tube, ACPT); describes the components of a proof-of-concept test of a Stirling cycle prototype using R-729 (air) as the refrigerant, heat exchange experiments, and heat transfer analyses; appendices present an electrical analog used to model the system, simplified modelling of the natural frequency, and an order-of-magnitude estimation by Helmholz model of the natural frequency; discussion of the paper offers estimates of key operating parameters including operating and Carnot coefficients of performance (COP) of 1 and 2, respectively

S. M. Sami, Y. Zhou, and M. Allam, **Numerical Prediction of Refrigerant Mixtures Condensation Inside Enhanced-Surface Vertical Cylinders**, *International Journal of Energy Research* (IJER), 18:799-811, 1994 (13 pages, rdb8606)

heat transfer in vertical heat exchangers for refrigerant blends assuming one-dimensional flow

H. Schömann, A. Luke, and D. Gorenflo (Universität Paderborn, Germany), **Size Distributions of Active Nucleation Sites with Pool Boiling Heat transfer at Single tubes with Different Roughness**, *Heat Transfer 1994* (proceedings of the Tenth International Heat Transfer Conference, Brighton, UK), Institution of Chemical Engineers (IChemE), Rugby, UK, 5:63-68, 1994 (6 pages, rdb9871)

nucleate boiling heat transfer: effects of surface finish

H. Schömann, **Beitrag zum Einfluß der Heizflächenrauhigkeit auf den Wärmeübergang beim Blasensieden** [Contribution of the Influence of Surface Finish on Heat Transfer in Nucleate Boiling], dissertation, Universität Paderborn, Germany, 1994 (rdb9869)

influence of surface roughness on bubble formation in nucleate boiling, heat transfer, evaporator, heat exchanger

H. Schönfeld and W. E. Krauss (Technische Universität Dresden, Germany), **Calculation and Simulation of a Heat Exchanger: Supercritical Carbon Dioxide - Water**, *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 72-80, 1997 (9 pages with 6 figures, RDB9806)

designs a model for design of refrigerant-water heat exchangers for use of R-744 (carbon dioxide) as a refrigerant

A. Schütz, **Strömungssieden in Rohren oder Kanälen: Die thermodynamisch optimale Strömungslänge** [Flow Boiling In Tubes and Channels: The Optimal Thermodynamic Flow Length], *DKV Jahrestagung* [Proceedings of the DKV Annual Meeting] (Bremen, Germany, 17 November 1992), *Deutscher Kälte- und Klimatechnischer Verein* (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, 279-296, 1992 (in German, rdb9414)

heat transfer

M. M. Shah (Gilbert/Commonwealth Company), **A General Correlation for Heat Transfer During Film Condensation Inside Pipes**, *International Journal of Heat and Mass Transfer*, 22:547-556, 1979 (10 pages, rdb9829)

widely cited correlation for condensing heat transfer

W. Shao and E. Granryd (Kungliga Tekniska Högskolan, KTH, Sweden), **Flow Condensation of Pure and Oil Contaminated Refrigerant HFC-134a in a Horizontal Tube**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 317-322, July 1994 (6 pages with 5 figures, RDB4840)

R-134a, Castrol ester-based lubricant

T. J. Sheer and S. R. Mitchley (University of Witwatersrand, South Africa), **Vacuum Boiling in a Water Vapour Refrigeration System**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 53-62, 1998 (10 pages with 7 figures, RDB9202)

describes tests of vacuum boiling (flashing) of R-718 (water) in direct-contact evaporators for potential use in refrigeration systems using water as the refrigerant to cool mines: presents tests of three evaporator designs including a through-flow, vertical cylinder, and narrow flow channel configurations, the last with flow visualization; describes the contributions of various boiling regimes to total heat transfer and presents the heat transfer coefficients (HTCs) obtained; concludes that the vacuum-boiling process is governed by a combination of water surface temperature and hydrostatic pressure gradient, which are in turn determined by flow geometry above the water surface and by convection heat transfer below the surface; includes discussion by A. Ophir (Ide Technologies Limited, Israel) and M. P. Maiya (Indian Institute of Technology at Madras, India)

K. Shi, E. Hahne, and U. Groß (Universität Stuttgart, Germany), **Pool Boiling Heat Transfer in HFC-134a, HFC-152a, and Their Mixtures**, paper 59,

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New Challenges in Refrigeration (proceedings of the XVIIIth International Congress of Refrigeration, Montreal, Québec, Canada, 10-17 August 1991), International Institute of Refrigeration, Paris, France, 11:459-463, 1991 (5 pages with 10 figures and 2 tables, RDB54A5)

nucleate pool boiling of R-134a, R-152a, and R-134a/152a on a platinum wire; scaling of the heat transfer coefficients to tubes; comparison to prior data for R-12

J. Y. Shin, M. S. Kim, and S. T. Ro (Seoul National University, Korea), **Experimental Study on Forced Convective Boiling Heat Transfer of Pure Refrigerants and Refrigerant Mixtures in a Horizontal Tube**, *International Journal of Refrigeration* (IJR), 20(4):267-275, June 1997 (9 pages with 9 figures and 2 tables, RDB8817)

measurement of convective heat transfer coefficients (HTCs) for R-22, R-32, R-134a, R-290, R-32/125, R-32/134a, R-290/600a in a smooth, stainless steel tube with an inside diameter of 7.7 mm (0.30") at 12 °C (54 °F); concludes that HTCs depend strongly on heat flux at low qualities, but become independent as the quality increases; also concludes that both the Güngör-Winterton correlation and the Thome-Shakil modification to it overestimate the HTCs

J. Y. Shin, M. S. Kim, and S. T. Ro (Seoul National University, Korea), **Correlation of Evaporative Heat Transfer Coefficients for Refrigerant Mixtures**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 151-156, July 1996 (6 pages with 4 figures and 1 table, RDB6829)

R-22, R-32, R-125, R-134a, R-290, R-600a, R-32/134a, R-290/600a, modification to Chen's correlation to predict heat transfer coefficients (HTCs)

M. Shoij, **Boiling Chaos and Modeling**, *Heat Transfer 1998* (proceedings of the 11th International Heat Transfer Conference, Kyongju), Taylor and Francis Publishers, Levittown, 1:3-21, 1998 (19 pages, rdb9859)

analysis of heat transfer, spatio-temporal behavior of surface superheat in the vicinity of nucleation sites, modeling of nucleation, evaporation, heat exchangers

M. Shoukri, R. J. Yanchis, and E. Rhodes, **Effect of Heat Flux on Pressure Drop in Low Pressure Flow Boiling in a Horizontal Tube,** *Canadian Journal of Chemical Engineering,* 59:149-154, 1981 (8 pages, rdb9415)

heat transfer and pressure drop measurements of R-718 (water) in smooth a steel tube

A. Singh, M. M. Ohadi, S. Dessiatoun, and W. Chu (University of Maryland), **In-Tube Boiling Heat Transfer Coefficients of R-123 and Their Enhancement Using the EHD Technique**, *Journal of Enhanced Heat Transfer*, 2(3):209-217, 1995 (9 pages, rdb7523)

R-123 exhibits excellent response to electrohydrodynamic (EHD) enhancement of heat transfer: tests in a tube-in-tube heat exchanger with hot water flowing in the outer tube and the test refrigerant flowing in the inner tube; experiments utilized a stainless steel cylindrical electrode of 3 mm (0.12") outside diameter placed coaxially in a smooth, stainless steel tube of 9.4 mm (0.37") inside diameter and 1.22 m (4') long; parametric tests with varying inlet quality, heat flux, and mass flux; EHD increased the heat transfer coefficient (HTC) as much as 550%; electrical power needed was less than 0.27% of the heat transfer rate

A. Singh, M. M. Ohadi, S. Dessiatoun, and W. Chu (University of Maryland), **In-Tube Boiling Heat Transfer Enhancement of R-123 Using the EHD Technique**, paper OR-94-10-3, *Transactions* (Annual Meeting, Orlando, FL, 25-29 June 1994), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 100(2):818-825, 1994 (8 pages with 12 figures, RDB4725)

applicability of electrohydrodynamic (EHD) enhancement of in-tube boiling heat transfer of R-123 in a tube-in-tube heat exchanger with hot water flowing in the outer tube and the test refrigerant flowing in the inner tube: experiment used a stainless steel cylindrical electrode with an outer diameter (OD) of 3 mm (0.118") placed coaxially in the test section, which was a 1.22 m (4') long, smooth, stainless steel tube with an inner diameter of 9.4 mm (0.37"); tests examined the effects of inlet quality, heat flux, and mass flux; concludes that R-123 exhibits an excellent response to the EHD effect, yielding a increases in the heat transfer coefficient (HTCs) as high as 550%; the electrical power consumption penalty was found to be less than 0.27% of the corresponding test section's heat transfer rate

K. Spindler, P. Englich, and E. Hahne (Universität Stuttgart, Germany), **Vergleich des Wärmeübergangs beim Behältersieden von R404A mit R22 an einem Hochleistungsrohr** [Comparison of the Pool Boiling Heat Transfer of R-404A to R-22 on a High Performance Tube], paper 21, *DKV-Tagungsberichte,* Deutscher Kälte- and Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, 24(II.I):150-168, 1997 (19 pages, rdb9867)

heat transfer of R-22 and R-404A

K. Spindler, **Flow Boiling**, *Heat Transfer 1994* (proceedings of the Tenth International Heat Transfer Conference, Brighton, UK), Institution of Chemical Engineers (IChemE), Rugby, UK, 1:349-368, 1994 (10 pages, rdb9422)

heat transfer

K. E. Starner (York International Corporation), **Heat Exchangers for Ammonia Water Chillers - Design Considerations and Research Needs**, *R-22 and R-502 Alternatives* (Proceedings of the ASHRAE/-NIST Refrigerants Conference, Gaithersburg, MD, 19-20 August 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 85-89, 1994 (5 pages with 2 figures and 4 tables, RDB4522)

R-717

D. Steiner, **Pool and Forced Convective Vaporization of Saturated Liquid Mixtures**, *Chemical Engineering and Processing*, 33(5):337-351, 1994 (16 pages, rdb9416)

heat transfer

D. Steiner and J. Taborek, **Flow Boiling Heat Transfer in Vertical Tubes Correlated by an Asymptotic Model**, *Heat Transfer Engineering*, 13(2):43-69, 1992 (27 pages, rdb9419)

heat transfer

K. Stephan (Universität Stuttgart, Germany), **Boiling in Multicomponent Mixtures,** in *International Encyclopedia of Heat and Mass Transfer*, edited by G. F. Hewitt, G. L. Shires, and Y. V. Polezhaev, CRC Press, New York, NY, 1997 (rdb9916)

heat transfer for blends

K. Stephan (Universität Stuttgart, Germany), **Heat Transfer in Condensation of Refrigerant Mixtures: Influence of Thermophysical Properties and Interfacial Effects**, *Proceedings of the International Seminar on Heat Transfer, Thermophysical Properties, and Cycle Performance of Alternative Refrigerants* (Tokyo, 1993), Nippon Reito Kyokai [Japanese Association of Refrigeration, JAR], Tokyo, Japan, 1-13, 1993 (13 pages, rdb9919)

heat transfer for blends

K. Stephan, H. Ettle, and D. Jump (Universität Stuttgart, Germany), **Free Convective Heat Transfer to a Binary Mixture Without Retrograde Condensation,** *Heat Transfer 1990* (proceedings of the Ninth International Heat Transfer Conference, Jerusalem, Israel), Hemisphere Publishing Corporation, New York, NY, 2:253-256, 1990 (4 pages, rdb9923)

condensing heat transfer, blends, heat exchangers

K. Stephan and P. Preusser (Universität Stuttgart, Germany), **Wärmeübergang und maximale Wärmestromdichte beim Behältersieden binärer und ternärer Flüssigkeitsgemische** [Pool Boiling Heat Transfer and Maximum Heat Flux Density of Binary and Ternary Fluid Mixtures], paper MS649/9, *Chem.-Ing. Techn.*, 1979; synopsis published in *Chem.-Ing. Techn.*, 51:37, 1979 (in German, rdb9865)

boiling heat transfer, evaporator

J. R. Thome (John Thome Incorporated), **Boiling and Evaporation of Fluorocarbon and Other Refrigerants: A State-of-the-Art Review**, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, October 1998 (128 pages with 54 figures and 3 tables, available from JMC as RDB9112)

review of heat transfer research for refrigerant boiling and evaporation based on a literature review and assessment, with emphasis on publications since 1995: covers in-tube and shell-side boiling of single-compound ("pure") refrigerants, azeotropic and zeotropic blends, and refrigerant-lubricant (RL) mixtures; addresses plain tubes, internally finned (microfin) tubes with conventional and cross-grooved fins, corrugated tubes, both conventional low fin and enhanced geometries of externally finned-tubes, and failing-film evaporation; this survey focuses on experimental studies, the accuracy of the tests, comparisons to similar studies, and reduction to design methods; report includes suggestions to improve experimental procedures, shortcomings of existing design methods, recommendations for their improvement, and future research needs; report is divided into discussion of previous literature surveys, nucleate pool boiling of single compounds and azeotropic blends, nucleate pool boiling of zeotropic blends, boiling on tube bundles, flow boiling of single compounds and azeotropic blends inside tubes, flow boiling of zeotropic blends inside tubes, flow boiling of RL mixtures inside tubes, and falling film evaporation; recommends development of a database on flow boiling, further tests of shell-side boiling of zeotropic mixtures, investigation of two-phase flow patterns for in-tube evaporation, study of two-phase pressure drops, and further tests of boiling on low-finned tubes; among the refrigerants addressed are R-11, R-12, R-22, R-113, R-114, R-123, R-134a, R-290 (propane), R-404A, R-407C, R-410A, R-600a (isobutane), R-717 (ammonia), R-744 (carbon

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dioxide), R-7146 (sulfur hexafluoride), R-22/142b, R-23/134a, R-32/134a, R-32/152a, R-290/600a, and R-290/600

J. R. Thome (John Thome Incorporated), **Condensation of Fluorocarbon and Other Refrigerants: A State-of-the-Art Review**, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, October 1998 (110 pages with 50 figures and 3 tables, available from JMC as RDB9113)

review of heat transfer research for refrigerant condensing based on a literature review and assessment: covers in-tube and shell-side condensing of single-compound ("pure") refrigerants, azeotropic and zeotropic blends, and refrigerant-lubricant (RL) mixtures; addresses plain tubes, internally finned (microfin) tubes with conventional and cross-grooved fins, and both conventional low fin and notched or otherwise enhanced geometries of externally finned tubes; also addresses research of two-phase pressure drop for in-tube condensation and developments in theoretical and empirical thermal design methods; this survey focuses on experimental studies, the accuracy of the tests, comparisons to similar studies, and reduction to design methods; report includes suggestions to improve experimental procedures, shortcomings of existing design methods, recommendations for their improvement, and future research needs; report is divided into discussion of previous literature surveys, tests of condensation on single tubes, analytical studies of condensation on single tubes, condensation with vapor shear and tube-row effects, condensation of blends on tubes and tube bundles, condensation of single-compounds and azeotropes inside tubes, condensation of zeotropes inside tubes, condensation of RL mixtures inside tubes, and two-phase pressure drops for in-tube condensation; recommends further tests of shell-side condensation of zeotropic mixtures, development and analysis of a database on tube-side condensation, modeling of local condensing coefficients and flow patterns in plain and microfin tubes, development of a generalized model to predict in-tube condensation for zeotropic blends, modeling of two-phase pressure drops, and preparation of algebraic equations to calculate the temperature-enthalpy-quality (THX) relationships for zeotropes; among the refrigerants addressed are R-11, R-12, R-22, R-32, R-113, R-114, R-123, R-124, R-125, R-134a, R-142b, R-143a, R-290 (propane), R-404A, R-407C, R-410A, R-502, R-507A, R-11/113, R-22/114, R-22/123, R-22/142b, R-22/152a, R-23/134a, R-32/134, R-32/134a, R-32/152a, R-125/22, and R-143a/-124

R. L. Webb and M. Zhang (Pennsylvania State University), **Prediction of Condensation and Evaporation in Micro-Fin and Micro-Channel Tubes**, *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 13-31, 1997 (19 pages with 9 figures, RDB9801)

survey of methods to predict condensation and evaporation heat transfer in plain, microfin, and microchannel tubes for hydraulic diameters as small as 1 mm (0.04"): presents a predictive model based on the two-phase heat-momentum transfer analogy to improve on the widely-used Shah correlation; provides comparisons to data for R-22, R-32, R-125, R-134a, and R-410A

R. L. Webb (Pennsylvania State University), **Advances in Modeling Enhanced Heat Transfer Surfaces,** *Heat Transfer 1994* (proceedings of the Tenth International Heat Transfer Conference, Brighton, UK), Institution of Chemical Engineers (IChemE), Rugby, UK, 1:445-460, 1994 (6 pages, rdb9827)

analysis of heat transfer

K. Yamashita and A. Yabe (Toshiba Corporation, Japan), **Electrohydrodynamic Enhancement of Falling Film Evaporation Heat Transfer and Its Long-Term Effect on Heat Exchangers**, *Journal of Heat Transfer*, 119:339-347, May 1997 (9 pages, rdb8849)

electrohydrodynamic (EHD) enhancement of heat transfer for evaporation of R-123 in a falling-film heat exchanger fabricated of stainless steel

E. G. Zaulichnyi and A. P. Yakushau (National Academy of Sciences of Belarus, Minsk, Belarus), **Energy and Resource Saving Systems Are the Alternative to Global Warming,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 180-190, 1998 (11 pages with 3 figures and 1 table, RDB9213)

describes a *vortical gas-energy dividing tube* (VGEDT) [a vortex tube refrigeration process] using R-729 (air) as the refrigerant; experimental data, industrial tests

X. Zeng, M. C. Chyu (Texas Tech University), and Z. H. Ayub (ThermalFluid International), **Ammonia Spray Evaporation Heat Transfer Performance of Single Low-Fin and Corrugated Tubes,** paper 4109 (SF-98-15-2, 725-RP), *Transactions* (Winter Meeting, San Francisco, CA, 17-21 January 1998), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 104(1A):185-196, 1998 (12 pages with 21 figures and 1 table, RDB8613)

evaporation of liquid R-717 sprayed onto a 19 mm (3/4") low-fin, horizontal, steel tube at saturation temperatures from -23.3 to 10 °C (-10 to 50 °F); effects of heat flux, saturation temperature, spray flow rate, nozzle spray angle, and nozzle height; comparisons to heat transfer coefficients (HTCs) for plain and corrugated tubes

X. Zeng (Valeo Climate Control), M. C. Chyu (Texas Tech University), and Z. H. Ayub (ThermalFluid International), **Performance of Nozzle-Sprayed Ammonia Evaporator with Square-Pitch Plain-Tube Bundle**, paper 4059 (725-RP), *Transactions* (Annual Meeting, Boston, MA, 28 June - 2 July 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 103(2):68-81, 1997 (14 pages with 17 figures and 1 table, RDB8522)

heat transfer of R-717 in spray evaporation on a horizontal bundle composed of 19.1 mm (3/4"), plain, stainless steel tubes at -23.3 to 10 °C (10 to 50 °F) and 164-615 kPa (23.7-89.2 psia): experiment was conducted using commercial nozzles distributing R-717 on a 3x3, square pitch, configuration with a pitch ratio of 1.25; heat transfer coefficients (HTCs) were determined for heat fluxes of 3.2 to 35 kW/m^2 (1,000-11,000 $Btu/h{\cdot}ft^2$); examines effects of heat flux, saturation temperature, spray flow rate, nozzle height, and nozzle type (standard or wide angle); compares heat transfer performance for spray evaporation and pool boiling; presents a correlation developed for the spray evaporation data; includes discussion by S. A. Moeykens (The Trane Company)

X. Zeng, M. C. Chyu (Texas Tech University), and Z. H. Ayub (Ayub and Associates, Incorporated), **Evaporation Heat Transfer Performance of Nozzle-Sprayed Ammonia on a Horizontal Tube**, paper 3845 (725-RP), *Transactions* (Winter Meeting, Chicago, IL, 28 January - 1 February 1995), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(1):136-149, 1995 (13 pages with 16 figures, RDB5239)

effects of heat flux, saturation temperature, spray flow rate, and nozzle height on boiling heat transfer for R-717: tests were conducted on a horizontal, plain, stainless steel tube at 23.3 to 10 °C (-10 to 50 °F) for heat fluxes of 8-60 kW/m^2 (2,500-19,000 $Btu/h{\cdot}ft^2$); both standard and wide-angle commercial nozzles were tested; compares results to measured pool boiling data and previously published findings

Y. Zhao, M. M. Ohadl, S. V. Dessiatoun, A. Schuster, A. McNair, R. K. Radermacher, and J. Darabi (University of Maryland), **Evaporation Heat Transfer Coefficients of Ammonia and CO_2 Inside a Smooth Tube**, *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 116-130, 1997 (15 pages with 7 figures and 3 tables, RDB9810)

measurements of the heat transfer coefficients (HTCs) in evaporation of R-717 (ammonia) and R-744 (carbon dioxide) in a horizontal, smooth, stainless steel tube with an inside diameter of 5.44 mm (0.21") and wall thickness of 1.27 mm (0.05") at 15 °C (59 °F); found that the HTC of R-717 was 10-15% higher for R-717 than R-744 at the same mass flow rate and heat flux and also higher than for R-22 and R-134a; notes that the HTC of R-744 will be comparable in practice due to the higher mass flux likely to be used

O. Zürcher, J. R. Thome, and D. Favrat (École Polytechnique Fédérale de Lausanne, ÉPFL, Switzerland), **Flow Boiling of Ammonia in Smooth and Enhanced Horizontal Tubes**, *Compression Systems with Natural Working Fluids* (proceedings of the IEA HPC Annex 22 Workshop, Gatlinburg, TN, 2-3 October 1997), International Energy Agency (IEA) Heat Pump Centre (HPC), Sittard, The Netherlands, 1997 (rdb8816)

flow boiling heat transfer of R-717

Applicability, Design Aspects, and Long-Term Effects of EHD Enhanced Heat Transfer of Alternative Refrigerants and Refrigerant Mixtures for HVAC Applications, research project 857-RP, American Society of Heating, Refrigerating, Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1995 - November 1997, extended to 1998 (ASH0857)

This project will investigate enhancement of boiling heat transfer by electrohydrodynamic (EHD) effects. The research focuses on concept testing, including experimentation and demonstration, and system design, including optimum electrode design and system design guidelines. The contractor is Texas A&M University led by J. Seyed-Yagoobi; the project is sponsored by ASHRAE Technical Committee 8.5, *Liquid to Refrigerant Heat Exchangers.*

Effects of Inundation and Miscible Oil Upon the Condensation Heat Transfer Performance of R-134a, research project 984-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1997 - April 1999 (ASH0984)

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This research will investigate the effect of liquid inundation and lubricant concentration on condensing heat transfer on the shell-side of shell-and-tube heat exchangers. It also will examine the benefits of surface enhancement for both single tubes and tube bundles. The report on the work will include a literature survey. The contractor for the project is Kansas State University (KSU) led by S. J. Eckels; it is sponsored by ASHRAE Technical Committee 8.5, *Liquid to Refrigerant Heat Exchangers*.

EHD-Enhanced Condensation Heat Transfer of Alternate Refrigerants and Refrigerant Mixtures for HVAC Applications, research project 922-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1996 - April 1998 (ASH0922)

This research will investigate the performance of electrohydrodynamic (EHD) techniques to enhance heat transfer with alternative refrigerants and blends. It also will provide data on pressure drop, electrical power requirements, electrode geometries, and operating conditions for air-conditioning and refrigeration applications. Utilizing these and other published data, the work will develop design correlations for feasibility and economic evaluation of EHD-enhanced condensation. The contractor for the project is the University of Maryland led by M. M. Ohadi; it is sponsored by ASHRAE Technical Committee 8.5, *Liquid-to-Refrigerant Heat Exchangers*.

Evaporation of Ammonia Outside Smooth and Enhanced Tubes With Miscible and Immiscible Oils, research project 977-RP, American Society of Heating, Refrigerating, Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1997 - April 1999 (ASH0977)

This research includes both a literature survey and measurements of R-717 (ammonia) heat transfer on both single tubes and tube bundles for horizontal tubes in flooded evaporators. Tests will evaluate both enhanced and smooth tubes, different flow and temperature conditions, and the effects of miscible and immiscible lubricants. The measured data will be reduced to correlations and charts for use in design. The contractor for the project is the Texas Technological University, led by M-C. Chyu; it is sponsored by ASHRAE Technical Committee 1.3, *Heat Transfer and Fluid Flow.*

Experimental Determination of Heat Transfer in Water-Cooled Condensers and Direct Expansion Water Coolers Using Brazed Plate Heat Exchangers, research project 752-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1994 - October 1996 (ASH0752)

This project will determine average heat transfer coefficients for R-22 and R-134a for counterflow plate heat exchangers. Two or more commercially-available, brazed-plate heat exchangers will be tested. Heat transfer coefficients will be measured for the refrigerants for condensing at 41 °C (105 °F) and evaporating at 2 °C (35 °F). Water-side coefficients also will be determined. The coefficients and associated pressure drops will be presented as functions of the mass flow rates, which will be varied over the full range of commercial applications. Superheating and subcooling effects also will be investigated. The overall goal is to provide basic information to permit potential users to evaluate counterflow, brazed-plate heat exchangers as refrigerant evaporators and condensers. The contractor is the University of Missouri at Columbia led by W. E. Stewart, H. J. Sauer, Jr., and B. R. Becker; the project is sponsored by ASHRAE Technical Committee 8.5, *Liquid to Refrigerant Heat Exchangers.*

Experimental Determination of the Effect of Oil on Heat Transfer in Flooded Evaporators with Refrigerants HCFC-123 and HFC-134a, research project 751-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1993 - April 1997, extended to 1998 (ASH0751)

This project will determine average shell-side boiling coefficients for R-123 and R-134a with compatible lubricants for finned and other enhanced tube surfaces, as used in flooded evaporators. The work will expand on that addressed in ASHRAE 392-RP, by covering the influences of the lubricants. Heat flux, mass flux, and vapor quality will cover typical conditions for air conditioning and refrigeration for lubricant concentrations of 0-10% at evaporator temperatures of approximately 4 °C (40 °F). The contractor is the Northern Illinois University, led by P. Payvar; it is sponsored by ASHRAE Technical Committee 8.5, *Liquid to Refrigerant Heat Exchangers.*

Heat Transfer and Pressure Drop Characteristics During In-Tube Gas Cooling of Supercritical Carbon Dioxide, research project 913-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1997 - December 1998 (ASH0913)

This research project will develop basic heat transfer and fluid flow data including local supercritical heat transfer coefficients (HTCs) for R-744 (carbon dioxide). It will examine improvements with enhanced-surface tubes and the effects of lubricants. The work also will develop correlations for use in design. The contractor for the project is Purdue University, led by E. A.

Groll; it is sponsored by ASHRAE Technical Committee 1.3, *Heat Transfer and Fluid Flow.*

In-Tube Evaporation of Ammonia in Smooth and Enhanced Tubes With and Without Miscible Oils, research project 866-RP, American Society of Heating, Refrigerating, Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1995 - October 1997, extended to 1998 (ASH0866)

This research project will investigate local, two-phase heat transfer and pressure drop during in-tube evaporation of R-717 (ammonia). Performance will be quantified for both a smooth tube and an enhanced-surface, micro-fin tube. The study also will examine the effect of miscible lubricants on evaporation performance. Correlations will be developed for use in design. The contractor for the project is Kansas State University (KSU) led by D. L. Fenton; it is sponsored by ASHRAE Technical Committee 1.3, *Heat Transfer and Fluid Flow.*

Single-Phase Refrigerant Heat Transfer and Pressure Drop Characterization of High Reynolds Number Flow for Internally Finned Tubes Including the Effects of Miscible Oils, proposed research project 1067-TRP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1999 - September 2001 (ASH1067)

This research project will develop nondimensional correlations to predict performance of internally-finned tubes for single-phase, refrigerant flows with Reynolds numbers of 5,000-1,000,000. The work will measure heat transfer coefficients (HTCs) and friction factors with 0.0, 0.5, 1.0, 3.0, and 5.0% m/m oil, to assess the impacts of lubricants. The work includes performance of a literature search and tests for both smooth and six types of internally finned copper tubes with outside diameters of 7.94 and 9.53 mm (0.32 and 0.38") for R-22, R-134a, R-407C, and R-410A. This research project is sponsored by ASHRAE Technical Committee 1.3, *Heat Transfer and Fluid Flow.* Proposals are due at ASHRAE Headquarters by 18 December 1998. Further information is available from the ASHRAE Manager of Research (+1-404/636-8400).

Indirect Systems ("Secondary Loops")

T. P. Castle, R. H. Green (EA Technology, UK), and D. Anderson (Lancaster University, UK), **Modelling of an Integrated Supermarket Refrigeration and Heating System Using Natural Refrigerants,** *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 363-368, July 1996 (6 pages with 5 figures, RDB6936)

simulation model for an integrated supermarket refrigeration and heating system using R-717 (ammonia) and hydrocarbons in indirect systems; secondary loop refrigeration systems

K. G. Christensen and M. Kauffeld (Dansk Teknologisk Institut, DTI, Denmark), **Heat Transfer Measurements with Ice Slurry**, *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 161-176, 1997 (16 pages with 15 figures and 4 tables, RDB9818)

heat transfer studies of ice slurry in shell-and-tube heat exchangers for use as a heat transfer fluid in indirect ("secondary-loop") systems for refrigeration; determination based on comparisons to a predetermined heat transfer coefficient (HTC) for R-134a in the exchanger; presents a correlation for calculation of the HTC; also determines an HTC for condensing R-744 (carbon dioxide), used to heat the melting ice slurry; indicates that the HTC calculated by Nusselt's theory is 10-15% higher than the measured one, possibly due to the influence of oil from the compressor used

G. Eggen (Gjettum AS, Norway) and K. Aflekt (Norwegian University of Science and Technology, NTNU, Norway), **Commercial Refrigeration with Ammonia and CO_2 as Working Fluids,** *Natural Working Fluids '98* proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 281-292, 1998 (12 pages with 8 figures and 1 table, RDB9223)

illustrates the comparative pipe diameters for supply and return lines for R-404A, R-744 (carbon dioxide), and a commercial heat transfer fluid (Dowtherm J) showing the advantage of R-744; compares the volumetric flow rates (swept volumes) and estimated power draw for four systems for low temperature refrigeration; they include a single-stage R-404A system, a two-stage R-717 (ammonia) system using R-744 (carbon dioxide) as a heat transfer fluid (secondary refrigerant), a cascaded system with R-744 in the low stage and R-717 in the high stage, and a two-stage R-744 system; compares heat transfer coefficients (HTCs) for R-22 and R-744; briefly describes a prototype system using the R-744 cascaded with R-717, but gives no per-

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formance data for it; includes discussion by B. Adamson (Refrigeration Engineering Pty Limited, Australia), G. Cojan Calor S.A., France), and P. Rivet (MC International SA, France)

T. Enkemann and H. Arnemann (Universität Hannover, Germany), **Investigation of CO_2 as a Secondary Refrigerant**, *New Applications of Natural Working Fluids in Refrigeration and Air Conditioning* (proceedings of the meeting of IIR Commission B2, Hannover, Germany, 10-13 May 1994), International Institute of Refrigeration (IIR), Paris, France, 1994 (RDB6933)

use of R-744 (carbon dioxide) as a heat transfer fluid in indirect ("secondary-loop") systems for commercial refrigeration

O. Florian, **Heat Transfer and Pressure Drop of Liquid Secondary Refrigerants**, MS thesis, Kungliga Tekniska Högskolan (KTH), Stockholm, Sweden, 1997 (rdb9817)

heat transfer and pressure drop data for heat transfer fluids for indirect (secondary-loop) refrigeration; fluids include aqueous solutions of ethylene glycol, propylene glycol, ethanol, methanol, ammonia, calcium chloride, lithium chloride, and potassium acetate, potassium formate as well as non aqueous Dowtherm J, Syltherm XLT, "HFE-7100", and d-limonene

H. Gentner (BMW AG, Germany), **Passenger Car Air Conditioning Using Carbon Dioxide as Refrigerant,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 303-313, 1998 (11 pages with 7 figures and 1 table, RDB9226)

summarizes the results of the Refrigeration and Automotive Climate Systems under Environmental Aspects (RACE) project, a collaborative effort by European automobile manufacturers and suppliers to investigate use of R-744 (carbon dioxide) for mobile air conditioning systems (MACS): the three-year effort under the auspices of the European Council for Automotive Research and Development (EUCAR) was sponsored by the European Community; the paper describes the transcritical cycle selected and wind-tunnel tests of a prototype and a reference system using R-134a; concludes that R-744 systems offer sufficient cooling capacity for comfort in all ambient conditions and have comparable fuel consumption to R-134a systems at steady-state operating conditions; also concludes that the R-744 system offers a lower total equivalent warming impact (TEWI) and that the estimated weight increase for it would have "no remarkable influence" on fuel consumption; addresses safety concerns with the pressure and toxicity of R-744; notes that further development is needed for the compressor and to reduce the costs of the internal heat exchanger, and the high-side pressure control; sensors for control and safety, and hoses with permeation barriers; indicates that more investigation is needed and that a switch to R-744 use will be possible only if there is agreement among all important markets and car manufacturers in the world; includes discussion by D. C. Zeitlow (Visteon, USA), V. W. Goldschmidt (Purdue University, USA), J. A. Baker (Delphi Automotive Systems Incorporated, USA), L. Asteberg (Ingenjörfirman Lennart Asteberg AB, Sweden), M. Paesante (KMP - Kenmore International, Italy), and M. Ghodbane (Delphi Automotive Systems Incorporated, USA)

H. Gentner and A. Födi (BMW AG, Germany), **Kohlendioxid als Kältemittel für Pkw-Klimaanlagen** [Carbon Dioxide as Refrigerant for Passenger Car Air Conditioning Systems], *Ki Luft- und Kältetechnik,* 34(1):19-24, January 1998 (6 pages in German, rdb9232)

summarizes the results of the Refrigeration and Automotive Climate Systems under Environmental Aspects (RACE) project, a collaborative effort by European automobile manufacturers and suppliers to investigate use of R-744 (carbon dioxide) for mobile air conditioning systems (MACS): the three-year effort under the auspices of the European Council for Automotive Research and Development (EUCAR) was sponsored by the European Community

U.. Hesse (Spauschus Associates, Incorporated), **Secondary Refrigerant Systems for Supermarket Application with Brine or Carbon Dioxide,** *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 369-376, July 1996 (8 pages with 8 figures and 4 tables, RDB6937)

evaluation of an organic salt and water solution, propylene glycol, ice slurry, and R-744 (carbon dioxide) as heat transfer fluids in indirect (secondary-loop) commercial refrigeration, supermarket systems; concludes that indirect systems are promising to avoid refrigerant leakage into supermarkets, organic salt solutions are more efficient than propylene glycol in high-temperature systems, and use of R-744 in a phase change or cascaded system is promising; cites defrost problems as a not insurmountable barriers as a heat transfer fluid

T. Hirata and K. Fujiwara (Denso Corporation, Japan), **Improvement of Mobile Air Conditioning System from Point of Global Warming Problems,** *Natural Working Fluids* '98 (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 314-323, 1998 (10 pages with 9 figures and 1 table, RDB9229)

addresses problems with use of hydrocarbons or R-744 (carbon dioxide) as alternatives to R-134a in automotive air-conditioning systems; compares the compressor displacements, theoretical coefficients of performance (COPs), operating pressures of R-290 (propane), R-600a (isobutane), and R-290/600 (propane/n-butane) to those of R-134a; concludes that propane is superior to R-134a in cooling capacity and practical (not theoretical) COP for optimized compressors; its flammability risk can be lowered with measures to reduce the charge size, which can be lowered to one-third of that for R-134a; discusses use of double-wall evaporators and secondary heat transfer fluids to further reduce the risk if leakage into the passenger compartment; notes that the COP for carbon dioxide is lower than for R-134a and the pressure evaporator seven times higher; suggests opportunities for performance improvement, but concludes that R-134a would still result in approximately 30% higher COP and has greater potential for further compressor optimization; compares the total equivalent warming impact (TEWI) of the options concluding that R-134a is highest at present, but can be reduced to the same level as carbon dioxide with both optimized, but that optimized hydrocarbon systems would be more favorable than either of them; notes concerns with conventional lubricants and elastomers for use with carbon dioxide and concerns with leakage due to its pressure; concludes that existing R-134a systems and recovery must be improved to provide more environmentally-friendly systems and that further consideration of alternatives is needed to reach an industry consensus

P. S. Hrnjak (University of Illinois at Urbana-Champaign), **The Benefits and Penalties Associated with the Use of Secondary Loops,** *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 85-95, 1997 (11 pages with 13 figures and 4 tables, RD137B10)

comparative advantages and disadvantages of direct and indirect (secondary loop) refrigeration systems: examination of single- and two-phase heat transfer fluids (coolants), the latter including both liquid-solid and gas-liquid types; summarizes results of laboratory experiments and modeling for commercial refrigeration systems for application in supermarkets; discusses ethylene and propylene glycol brines, silicone oils, organic salts, hydrofluoroethers (HFEs), ethanol-water mixtures, d-limonene, ice slurries, carbon dioxide; notes that indirect systems are particularly suited for lower operating temperatures in the range of -40 to 10 °C (-40 to 50 °F); concludes that the performance penalties of indirect systems can be overcome by reduced parasitic losses and refrigerant charge

C. A. Infante Ferreira and S. Soesanto (Delft University of Technology, The Netherlands), **CO_2 in Comparison with R404A,** *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 141-149, 1997 (19 pages with 12 figures, RDB9813)

compares the performance of low-temperature, commercial refrigeration systems using R-404A and R-404A with a secondary loop using R-744 (carbon dioxide) as a phase change, heat transfer fluid; presents experimental data and simulations; concludes that the secondary-loop approach enjoys heat transfer advantages, but notes that defrosting of the carbon dioxide cooler requires controlled liquid injection when the cooler is at high temperature; also concludes that the simple and secondary-loop approaches result in approximately the same energy use

S. W. Inlow and E. A. Groll (Purdue University), **A Performance Comparison of Secondary Refrigerants**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 357-362, July 1996 (6 pages with 6 figures and 1 table, RDB6932)

performance comparison of R-744 (carbon dioxide), ethylene glycol, propylene glycol, undisclosed hydrofluoroether, and an undisclosed synthetic organic fluid as heat transfer fluids in secondary-loop commercial refrigeration, supermarket systems; concludes that a system using R-717 (ammonia) as a refrigerant with R-744 as a heat transfer fluid offers a coefficient of performance equivalent to that for R-22

S. W. Inlow and E. A. Groll (Purdue University), **Analysis of Secondary-Loop Refrigeration Systems Using Carbon Dioxide as a Volatile Secondary Refrigerants**, *HVAC&R Research,* 2(2):107-121, 1996 (15 pages, RDB6934)

use of R-744 (carbon dioxide) as a heat transfer fluid in indirect (secondary-loop) commercial refrigeration

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M. Kauffeld, **Neue NH_3-Technologie - NH mit CO_2 als Kaltetrager** [New Ammonia Technology - Ammonia with Carbon Dioxide as a Secondary Refrigerant], *Ki Klima-Kälte-Heizung*, Germany, 931-932, 1995 (2 pages in German, rdb6935)

use of R-744 (carbon dioxide) as a heat transfer fluid in indirect (secondary-loop) commercial refrigeration with R-717 (ammonia) as the primary refrigerant

T. P. McDowell (Thermal Storage Applications Research Center, TSARC), J. W. Mitchell, and S. A. Klein (University of Wisconsin), **Investigation of Ammonia-Secondary Fluid Systems in Supermarket Refrigeration Systems**, paper 3923, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):486-496, 1995 (11 pages with 9 figures and 2 tables, RDB6361)

indirect systems for refrigeration with R-717 (ammonia): optimization, performance comparison with staged compression to R-22 direct systems: compares three methods of staging the compression for both refrigerants; evaluates six secondary fluids for use with R-717; discusses rules based on the heat transfer fluid used for optimal systems design; concludes that the efficiency of well-designed secondary-loop systems with R-717 refrigeration is 4-10% lower than direct R-22 systems operating under similar conditions

Å. Melinder (Kungliga Tekniska Högskolan, KTH, Sweden), **Heat Transfer and Other Characteristics of Low Temperature Liquid Secondary Refrigerants**, *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 150-160, 1997 (11 pages with 6 figures, RDB9814)

application information on heat transfer fluids for indirect (secondary-loop) refrigeration; data includes the freezing point, viscosity, volume flow, volumetric heat capacity, Reynolds number, and heat transfer factors and pressure drops for laminar and turbulent flows; fluids include aqueous solutions of ethylene glycol, propylene glycol, ethanol, methanol, ammonia, calcium chloride, lithium chloride, and potassium acetate, potassium formate as well as non aqueous Dowtherm J, Syltherm XLT, "HFE-7100", and d-limonene; concludes that no single heat transfer fluid is ideal for all uses and provides selection guidance for anticipated application conditions

Å. Melinder (Kungliga Tekniska Högskolan, KTH, Sweden), **Thermophysical Properties of Liquid Secondary Refrigerants,** International Institute of Refrigeration (IIR), Paris, France, 1997 (rdb9816)

application information on heat transfer fluids for indirect (secondary-loop) refrigeration; fluids include aqueous solutions of ethylene glycol, propylene glycol, ethanol, methanol, ammonia, calcium chloride, lithium chloride, and potassium acetate, potassium formate as well as non aqueous Dowtherm J, Syltherm XLT, "HFE-7100", and d-limonene

Å. Melinder (Kungliga Tekniska Högskolan, KTH, Sweden), **Thermophysical Properties of Liquid Secondary Refrigerants - Charts and Tables**, handbook 12 (second edition), Swedish Society of Refrigeration, Stockholm, Sweden, 1997 (rdb9815)

application information on heat transfer fluids for indirect (secondary-loop) commercial refrigeration; fluids include aqueous solutions of ethylene glycol, propylene glycol, ethanol, methanol, ammonia, calcium chloride, lithium chloride, and potassium acetate, potassium formate as well as non aqueous Dowtherm J, Syltherm XLT, "HFE-7100", and d-limonene

W. Terrell, Jr., Y. Mao, and P. S. Hrnjak (University of Illinois at Urbana-Champaign), **Tests of Supermarket Display Cases when Operating with Secondary Refrigerants,** *Proceedings of the International Conference on Ozone Protection Technolo*gies (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 176-186, November 1997 (11 pages - one repeated - with 9 figures, RDB8343)

laboratory tests of potassium formate and potassium acetate brines in a upright display case with comparisons to a direct-expansion system using R-404A: discussion of alternative heat transfer fluids including silicone oils such as polydimethylsiloxane and unidentified hydrofluoroethers (HFEs); results for the display cases only (not the full systems) show improved performance with potassium formate at low temperatures

Operation and Maintenance

Guidelines for Start-Up, Inspection and Maintenance of Ammonia Mechanical Refrigerating Systems, bulletin 110, International Institute of Ammonia Refrigeration (IIAR), Washington, DC, March 1993 (60 pages with 7 tables, RDB4759)

This bulletin outlines basic requirements for the safe start-up, inspection, and maintenance of R-717 (ammonia) refrigerating systems. The maintenance focus is on steps to promote safety, to supplement manufacturer instructions. The guide provides definitions and a section on ammonia characteristics, properties, hazards, specifications for refrigerant grade ammonia, and general precautions. It then identifies essential records and documentation to be obtained and maintained by the user. A section on start-up covers an advance safety review, process hazard analysis, operating procedures, training, initial status and safety provisions, electrical equipment, evacuation, dehydration, leak checking, charging, and testing of protection devices. A section on inspection and maintenance covers general considerations, keeping of a system log, compressors, other system components, ammonia pumps, valves and sensing devices, piping, oil maintenance and removal, and motors and other drives. Appendices identify minimum design pressures, information to be provided on component name plates, a check list for start-up, and requirements for machinery rooms and auxiliary safety equipment. A separate appendix reviews stress corrosion cracking (SCC), inspection, and preventive measures. Additional appendices cover pressure tests and typical schedules for inspection and maintenance. The document concludes with sample forms for pressure vessel records and system logs.

Guidelines for Identification of Ammonia Refrigeration Piping and System Components, IIAR bulletin 114, International Institute of Ammonia Refrigeration (IIAR), Washington, DC, September 1991 (20 pages with 2 figures and 1 table, RDB4761)

This bulletin provides guidance for uniform labeling of R-717 (ammonia) piping and components for refrigeration systems. Its objective is to promote safety, facilitate maintenance, and provide vital information to emergency service personnel. It stipulates standardized identification of the physical state, relative pressure level, and direction of flow of the refrigerant for piping mains, headers, and branches. It also provides for identification of components, including receivers, heat exchangers, and accumulators. The bulletin prescribes standard piping and component markers with specific attention to content, arrangement, approved abbreviations, dimensions, and colors. It also prescribes marker locations and provides for posting of reference charts.

Performance

D. B. Bivens, D. M. Patron, and A. Yokozeki (DuPont Fluoroproducts), **Performance of R32/R-125/-R-134a Mixtures in Systems with Accumulators or Flooded Evaporators,** paper PH-97-9-4, *Transactions* (Winter Meeting, Philadelphia, PA, 26-29 January 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 103(1):777-780, 1997 (4 pages with 3 figures and 5 tables, RDB7C17)

R407 series blends

P. A. Domanski (National Institute of Standards and Technology, NIST), **Minimizing Throttling Losses in the Refrigeration Cycle,** *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:766-773, 1995 (8 pages with 12 figures, rdb7917)

performance of single-compound refrigerants in the basic reversed-Rankine and three modifications to minimize throttling-process (expansion) irreversibilities: concludes that all refrigerants can offer the same coefficient of performance (COP) in the ideal vapor-compression cycle; overall, the penalties from the expansion process are the largest total loss from the theoretical cycle; cycles with a liquid-line/suction line heat exchanger (llsl-hx or LSHX) minimize expansion losses for refrigerants with high molar heat capacity, but fluids with low molar heat capacity do not benefit from this enhancement; economizer cycles improve the performance for all refrigerants and reduce the COP differences among them, but fluids with the highest COP in the Rankine cycle are still the best performers; the COPs with ejector cycles are sensitive to the ejector efficiency; at low ejector component efficiencies, low heat capacity refrigerants have a better COP; at high ejector efficiencies, high heat capacity fluids show a higher COP; the improvements for both economizer and ejector cycles results from both increased capacity and reduced work, the latter having a more significant effect; refrigerants addressed include R-11, R-12, R-13, R-13B1, R-14, R-21, R-22, R-23, R-32, R-113, R-114, R-115, R-123, R-123a, R-124, R-125, R-134, R-134a, R-E134, R-141b, R-142b, R-143, R-143a, R-152a, R-218, R-227ea, R-236ea, R-245cb, R-E245, R-C270, R-290 (propane), R-C318, R-600 (n-butane), R-600a (isobutane), R-602 (n-pentane, n-C5), R-602a (isopentane, i-C5), R-717 (ammonia), R-744 (carbon dioxide)

P. A. Domanski, **Theoretical Evaluation of the Vapor Compression Cycle with a Liquid-Line/-Suction-Line Heat Exchanger, Economizer, and Ejector**, report NISTIR 5606, National Institute of Standards and Technology (NIST), Gaithersburg, MD, March 1995 (42 pages with 27 figures and 1 table, available from JMC as RDB6436)

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This report presents a theoretical analysis of three vapor-compression cycles that incorporate a liquid-line/suction-line heat exchanger (LSHX), economizer, or ejector. These enhancements reduce throttling losses by different principles, but they also increase complexity and costs. The analyses compared the variations to basic reverse Carnot and Rankine cycles for 38 refrigerants. They included R-11, R12, R-13, R-13B1, R-14, R-21, R-22, R-23, R-32, R-113, R-114, R-115, R-123, R-123a, R-124, R-125, R-134, R-E134, R-134a, R-141b, R-142b, R-143, R-143a, R-152a, R-218, R-227ea, R-236ea, R-245cb, R-E245, R-C270, R-290, R-C318, R-600, R-600a, R-601 (pentane), R-601a (isopentane), R-717, and R-744. The benefits of the cycle modifications generally increase with the amount of throttling losses realized by the refrigerant in the reverse-Rankine cycle. The study found that the LSHX cycle offers the smallest improvement. The ejector cycle offers the highest, but requires an ejector efficiency beyond that practically demonstrated. The performance of the ejector cycle is comparable to that of the single-stage economizer cycle for typical ejector efficiencies. The report includes a tabular summary of selected properties (critical temperature, molecular mass, latent heat of vaporization, and vapor and liquid molar heat capacities).

D. S. Godwin and M. S. Menzer (Air Conditioning and Refrigeration Institute, ARI), **HCFC-22 Phase Out in North America - Impact on Future Equipment Protection**, *IEA Heat Pump Newsletter - CFC and HFC Replacement,* International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, 13(1):29-31, March 1995 (3 pages with 2 figures and 1 table, RDB5689)

Alternative Refrigerants Evaluation Program (AREP)

K. Hachisuka, M. Kawada, and N. Ohya (Mitsubishi Heavy Industries, Limited, Japan), **Performance of R-125/143a/134a Low Temperature Refrigeration**, paper 3.2, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 52-56, December 1994 (5 pages with 12 figures and 2 tables; in Japanese with abstract, figures, and tables in English; RDB5411)

R-125/143a/134a (44/52/4) [R-404A], condensing unit with scroll compressor

A. Hafner, J. Pettersen, G. Skaugen, and P. Nekså (SINTEF Energy Research, Norway), **An Automobile HVAC System with CO_2 as the Refrigerant,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 335-345, 1998 (11 pages with 12 figures and 4 tables, RDB9231)

presents simulations of an automotive air conditioner using R-744 (carbon dioxide) as the refrigerant in a transcritical cycle; notes that the predicted coefficient of performance (COP) exceeds by 15% published test results from the European Council for Automotive Research and Development (EUCAR) Refrigeration and Automotive Climate Systems under Environmental Aspects (RACE) project; ascribes the difference to an improved design for the heat exchangers; indicates that a laboratory prototype is under construction for verification; includes discussion by G. Cogan (Calor S.A., France), M. Ghodbane (Delphi Automotive Systems Incorporated, USA), and V. W. Goldschmidt (Purdue University, USA)

G. H. Haines, T. W. Dekleva, and R. E. Low (ICI Klea), **Performance Testing of R-502 Replacements Based on R-32/R-125/R-134a,** *Proceedings of the 1994 International Refrigeration Confer*ence *at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 395-400, July 1994 (6 pages with 10 figures, RDB4852)

R-407A [R-32/125/134a (20/40/40)], R-407B [R-32/125/134a (10/70/20)]

M. Kurokawa, K. Nasako, M. Honjo, and M. Osumi (Sanyo Electric Company, Limited, Japan), **An Experimental and Theoretical Study on System Performance of Refrigeration Cycle Using Alternative Refrigerants**, *Proceedings of the 1996 International Refrigeration Conference of Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 217-222, July 1996 (6 pages with 9 figures and 3 tables, RDB6854)

R-410A, pressure loss in grooved tube evaporators, capillary tube characteristics, system simulation, seasonal performance, comparison to R-22 concludes that efficiency is better at low loads, worse at high loads, and nearly the same on a seasonal basis

S-M. Liao (Changsha Railway University, China) and A. Jakobsen (Danmarks Tekniske Højskole, DTH, Denmark), **Optimal Heat Rejection Pressure in Transcritical Carbon Dioxide Air Conditioning and Heat Pump Systems**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 346-356, 1998 (11 pages with 9 figures, RDB9233)

presents a method to determine the refrigerant pressure in the gas cooler for heat rejection to maximize efficiency in a transcritical cycle using R-744 (carbon dioxide); paper shows that the optimal pressure mainly depends on the outlet temperature of the gas cooler, the evaporation temperature, and the compressor efficiency; provides general correlations based on simulations for design and control of R-744 transcritical cycles; includes discussion by I. Strømmen (Norwegian University of Science and Technology, NTNU, Norway) and H. Quack (Technische Universität Dresden, Germany)

R. E. Low, J. D. Morrison, and F. T. Murphy (ICI Klea, UK), **Performance Testing of R-22 and R-502 Alternatives Based on R-32/R-125/R-134a,** paper 1.2, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 7-11, December 1994 (5 pages with 4 figures and 2 tables, RDB5402)

R-407A, R-407B, R-407C, R-32/125/134a, zeotropic blends, fractionation, performance, thermodynamics, servicing

I. L. Maclaine-cross and E. Leonardi (University of New South Wales, Australia), **Why Hydrocarbons Save Energy**, *AIRAH Journal,* Australian Institute of Refrigeration, Air Conditioning and Heating, West Melbourne, ACN, Australia, 33 and 35-38, June 1997 (5 pages with 4 tables, RDB8365)

comparison of the environmental impacts, measured energy use in domestic refrigerators, capacity and coefficient performance (COP) in heat pumps, calculated performance, and properties for R-12, R-22, R-134a, R-290 (propane), R-600a (isobutane), and R-717 (ammonia): indicates that hydrocarbons sometimes offer energy savings of 20% or more and that R-600a offers advantages in terms of reduced leakage, pressure loss, and heat transfer compared to R-12 and R-134a; projects future use of R-600a in systems with capacities below 5 kW (1.4 ton) and in automobile air conditioners, then R-290 up to 50 kW (14 ton), and R-717 in larger systems

Y. Morikawa (Matsushita Electric Industrial Company Limited, Japan), **Summary of Test Data from Several Drop-In, Compressor Calorimeter, Soft-Optimized Compressor, and Soft-Optimized System Tests Performed by JRAIA Member Companies,** Alternative Refrigerants Evaluation Program (AREP) report 123, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, October 1993 (14 pages with 10 figures and 1 table, available from JMC as RDB3D23)

Y. Morikawa (Matsushita Electric Industrial Company Limited, Japan), **R-22, R-502 Alternative Refrigerants Evaluation Program in Japanese Industry,** *R-22 and R-502 Alternatives* (Proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 19-20 August 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 31-39, 1994 (9 pages with 19 figures and 3 tables, RDB-4518)

P. Nekså (SINTEF Energy Research, Norway) S. Girotto (Costan S.p.A., Italy), and O. M. Schiefloe (SINTEF), **Commercial Refrigeration Using CO_2 as Refrigerant - System Design and Experimental Result**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 270-280, 1998 (11 pages with 8 figures and 2 tables, RDB9222)

presents simulations of supermarket refrigeration systems using R-744 (carbon dioxide) as the refrigerant in transcritical cycles; discusses heat recovery for service water and space heating; summarizes laboratory measurements of two self-contained display cases; compares simulated performance to R-22 systems based on assumed (no basis given) R-22 performance functions; differences between measured and simulated case efficiency attributed to lower compressor performance, suboptimal operation, and insufficient insulation; includes discussion by P. Rivet (MC International SA, France), H. Halozan (Technische Universität Graz, Graz, Austria), and P. D. Fairchild (Oak Ridge National Laboratory, ORNL, USA)

J. Pettersen (University of Illinois at Urbana-Champaign), **Experimental Results of Carbon Dioxide in Compression Systems**, *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 27-37, 1997 (11 pages with 13 figures and 4 tables, RDB7B04)

experimental and analytical findings for a prototype system and key components for use of R-744 (carbon dioxide): concludes that competitive efficiencies can be achieved for heating

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and heat recovery on a seasonal basis with optimized transcritical systems; notes that achieving high performance depends on minimizing approach temperatures, improving compressor efficiency, and designing for varying operating conditions and climates; tabulates simulations for outdoor heat exchangers and of volumetric losses in compressors for R-22 and R-744; illustrates comparative capacity and coefficients of performance (COP) for R-22, R-134a, and R-744

T. Yamaguchi (Mitsubishi Electric Corporation, Japan), **Characteristics of Scroll Condensing Units for R125/143a/134a**, paper 3.4, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 63-67, December 1994 (5 pages with 13 figures and 1 table; in Japanese with abstract, figures, and table in English; RDB5413)

R-125/143a/134a (44/52/4) [R-404A], composition shift, equilibrium composition, discharge temperature, cooling capacity and efficiency

Cycle Analyses

S. Bobbo, R. Camporese (Consiglio Nazionale delle Ricerche, CNR, Italy), G. Cortella (Università di Udine, Italy), and W. Fronasieri (Università di Padova, Italy), **Theoretical Evaluation of the Performance of Zeotropic Mixtures in Refrigerating Cycles**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:72-79, 1995 (8 pages with 5 figures and 2 tables, rdb7727)

use of the thermodynamic mean temperature (defined as the enthalpy variation divided by the entropy variation) to evaluate the performance of zeotropic mixtures in vapor-compression cycles to address the influence of temperature glide: illustration with a comparison of R-407C to R-22 for two applications in air conditioners and one in cold storage

C. E. Bullock (Carrier Corporation), **Theoretical Performance of Carbon Dioxide in Subcritical and Transcritical Cycles**, *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 20-26, 1997 (7 pages with 8 figures and 4 tables, RDB7B03)

examines the reasons for the low cycle efficiency of R-744 (carbon dioxide): analyzes theoretical and real cycles as well as cycle modifications to improve this performance; tabulates comparative efficiencies of R-22, R-134a, R-290, R-410A, R-717, and R-744; details an evaluation of R-744 in a 13.5 kW (4 ton) air-to-air unitary heat; concludes that R-744 offers the advantages of low toxicity, environmental attraction, nonflammability, and low cost but its inherently low efficiency and high operating pressures remain serious challenges; identifies needed improvements in heat exchangers, compressors, and expanders to make R-744 use competitive, and notes that the resulting higher discharge temperatures would make it attractive for use in heat pumps

S. Chen, J. F. Judge, E. A. Groll, and R. K. Radermacher (University of Maryland), **Theoretical Analysis of Hydrocarbon Mixtures as a Replacement for HCFC-22 for Residential Uses,** *Proceedings of the 1994 International Refrigeration Conference at Purdue,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 225-230, July 1994 (6 pages with 4 figures and 2 tables, RDB4827)

R-22, R-290 (propane), R-600 (n-butane), R-600a (isobutane), R-601a (isopentane), R-290/600, R-290/600a, R-290/601a

P. A. Domanski, D. A. Didion, W. J. Mulroy (National Institute of Standards and Technology, NIST, USA), and J. A. R. Parise (Pontifícia Universidade Católica do Rio de Janeiro, Brazil), **A Simulation Model and Study of Hydrocarbon Refrigerants for Residential Heat Pump Systems,** *New Applications of Natural Working Fluids in Refrigeration and Air Conditioning* (proceedings of the meeting of IIR Commission B2, Hannover, Germany, 10-13 May 1994), International Institute of Refrigeration (IIR), Paris, France, 339-354 1994 (16 pages with 5 figures and 7 tables, RDB5B28)

R-22, R-32/125 (49/51), R-290, R-290/600a (70/30), simulated performance

P. A. Domanski and D. A. Didion (National Institute of Standards and Technology, NIST), **Theoretical Evaluation of R22 and R502 Alternatives**, report DOE/CE/23810-7, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, January 1993 (32 pages with 19 figures and 7 tables, available from JMC as RDB3305)

This report. evaluates performance of candidate refrigerants to replace R-22 and R-502. The alternatives compared to R-22 include R-32/125 (60/40), R-407B [R-32/125/134a (10/70/20)], R-32/125/134a (30/10/60), R-32/125/290/134a (20/55/5/20), R-32/134a (25/75), R-32/134a (30/70), R-32/227ea (35/65), R-134a, and R-290 (propane). The analyses are based on a semi-theoretical model, CYCLE-11, with cross-flow heat transfer in the evaporator and condenser. Thermodynamic properties were calculated using the Carnahan-Starling-DeSantis (CSD) equation of state. The conditions examined approximate outdoor rating conditions for residential heat pumps, namely 27.8 and 35 °C (82 and 95 °F) for cooling and -8.3 and 8.3 °C (17 and 47 °F). Calculated volumetric capacities, coefficients of performance (COPs), pressure lift, and compressor discharge temperatures and pressures are plotted. The analyses are presented for "drop-in" conditions (constant heat exchangers), constant heat exchanger loading, and with addition of a liquid-suction heat exchanger. The alternatives compared to R-502 are R-32/125/143a (10/45/45), R-125/143a (45/55), and R-125/143a/134a (44/52/4) [R-404A]. These fluids are examined at typical conditions for commercial refrigeration, namely -23.3 and 35 °C (-10 and 95 °F) for the fluid entering the evaporator and condenser, respectively. Simulation cases and results similar to those for the R-22 alternatives are presented. Summary fluid properties and results for the constant exchanger loading cases are tabulated. They indicate efficiency losses of 1-16% for the R-22 alternatives and 3-7% for the R-502 alternatives. Corresponding changes in volumetric capacity range from 31% lower to 55% higher and from 8% lower to 13% higher than R-22 and R-502, respectively. The report notes, however, that these findings would change with consideration of differences in transport properties. The report abstractly discusses the influence of critical temperature on performance and unavoidable trade off between COP and volumetric capacity. It also reviews the impacts of heat capacity, liquid thermal conductivity, and liquid viscosity; neither these transport properties nor toxicity and flammability were otherwise addressed. Two appendices summarize the nomenclature used in the report and describe the CYCLE-11 model. A third tabulates vapor heat capacity, liquid and vapor thermal conductivity, and liquid and vapor viscosity for the fluids addressed.

I. W. M. Eames (University of Nottingham, UK) and M. Naghashzadegan (University of Sheffield, UK), **Comparison Study of Isceon 49 (A Drop-In Replacement for R12) with R12 and R-134a,** *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 259-264, July 1996 (6 pages with 8 figures and 1 table, RDB6911)

R-12, R-134a, R-413A, cooling capacity, coefficient of performance, cycle analysis, experimental validation in a refrigerator; concludes that retrofit from R-12 to R-413A does not result in a significant loss in overall performance

C. Meurer and H. König (Solvay Fluor und Derivate GmbH, Germany), **Effects of Accelerated Phase-Out Scenarios on Options to Replace R22 in Heat Pumps,** *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 13, 1999 (10 pages with 7 figures and 3 tables, RDB9845)

compares R-134a, R-290 (propane), R-407C, and R-410A as alternatives for R-22; presents measured compressor performance data for these refrigerants; provides cost analyses for substitution of the four alternative refrigerants; discusses the influence of regulations and standards on refrigerant selection; concludes that while R-410A offers a favorable option based on efficiency and costs, the preferred replacement option strongly depends on the phaseout schedule; paper notes that R-407C is gaining use in countries with early R-22 phaseout deadlines such as Sweden; near-term phaseouts, such as those in countries adhering the European Community schedule, favor R-407C since there is not adequate time to develop equipment for R-410A, but countries with more liberal schedules, such as Japan and the USA, are likely to embrace R-410A

S. N. Park and M. S. Kim (Seoul National University, Korea), **Performance of Autocascade Refrigeration System Using Carbon Dioxide and R134a**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 357-367, 1998 (11 pages with 13 figures, RDB9236)

presents cycle analyses of R-744/134a (10/90) and (30/70); also summarizes experimental performance measurements for R-744/134a (24/76) and (36/64); explains the rationale for use of R-744 (carbon dioxide) and R-134a blends; includes discussion by P. Rivet (MC International SA, France) and R. K. Radermacher (University of Maryland)

R. Rieberer and H. Halozan (Technische Universität Graz, Graz, Austria), **CO_2 Heat Pumps in Controlled Ventilation Systems,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 212-222, 1998 (11 pages with 10 figures, RDB9215)

outlines development of methods to optimize components for and predict the efficiency of

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heat pumps for exhaust air heat recovery to heat buildings and service water for them; suggests a seasonal performance factor (SPF) of 6.1-6.5 for the climate of Graz, Austria; includes discussion by A. Cavallini (Università di Padova, Italy), A. Hohla (Salzburger Aktiengesellschaft für Energiewirtschaft, SAFE, Austria), and M. S. Kim (Seoul National University, Korea)

J. Yin, Y. C. Park, D. Boewe, R. McEnaney, A. Beaver, C. W. Bullard, and P. S. Hrnjak (University of Illinois at Urbana-Champaign), **Experimental and Model Comparison of Transcritical CO_2 versus R134a and R410** [sic, R410A] **System Performance**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 376-387, 1998 (12 pages with 4 figures and 6 tables, rdb9240)

compares the performance of transcritical systems using R-744 (carbon dioxide) to R-134a for mobile air conditioning systems (MACS) and to R-410A for residential, air-to-air heat pumps; presents the experimental approach and preliminary results; notes that comparisons would only be conclusive if the systems compared are designed to meet the same cost and performance targets, since conventional MACS are designed to achieve low costs and small size rather than maximum efficiency; indicates that experimental results will be used to validate models to enable consistent comparisons; includes discussion by V. W. Goldschmidt (Purdue University, USA), P. A. Domanski (National Institute of Standards and Technology, NIST), D. C. Zeitlow (University of Illinois at Urbana-Champaign), H. Gentner (BMW AG, Germany), and J. Wertenbach (Daimler-Benz AG, Germany)

Compressor Calorimeter Tests

R. R. Angers (Dunham-Bush, Incorporated), **Compressor Calorimeter Test of Refrigerant Blend R-32/125 (50/50)**, Alternative Refrigerants Evaluation Program (AREP) report 182, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, May 1994 (14 pages with 8 figures and 2 tables, available from JMC as RDB5682)

R-410A compared to R-22, with a polyolester (POE) lubricant (CPI® Solest® 120), in a gas cycle test of a semihermetic, twin-screw compressor (Dunham-Bush 1615DHR4VOEOEM)

R. R. Angers (Dunham-Bush, Incorporated), **Compressor Calorimeter Test of Refrigerant R-134a** Alternative Refrigerants Evaluation Program (AREP) report 132, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, December 1993 (14 pages with 8 figures and 2 tables, available from JMC as RDB3D32)

This report presents results of calorimeter (gas-cycle) testing for two refrigerants in an open-drive, large twin screw compressor (Dunham-Bush model 1610FHF4VOE). R-22 was tested as a reference with a mineral oil (Witco Suniso® 4GS); R-134a was tested with a polyolester (CPI® Solest® 120). The report summarizes the test conditions and provides a schematic of the test system. Three appendices present the tabular data, derived performance curves, and a plot comparing the relative efficiencies for R-134a to those with R-22. The tabular data for the tests include capacity, input shaft power, energy efficiency ration (EER), coefficient of performance (COP), and relative COP (R-134a to R-22). The tests were performed at saturated suction temperatures of -7, -1, and 4 °C (20, 30, and 40 °F) and saturated discharge temperatures of 35 and 52 °C (95 and 125 °F). Capacity, input power, and COP are plotted for the same conditions. The resultant data for R-134a show 17% lower to 5% higher efficiency, depending on the suction and discharge temperatures. The relative COP appears to decrease with increasing lift. No source is indicated for the thermodynamic properties used.

R. R. Angers (Dunham-Bush, Incorporated), **Compressor Calorimeter Test of Refrigerant Blend R125/143a (50/50)**, Alternative Refrigerants Evaluation Program (AREP) report 133, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, December 1993 (14 pages with 8 figures and 2 tables, available from JMC as RDB3D33)

This report presents results of calorimeter (gas-cycle) testing for two refrigerants in a hermetic, vertical, twin screw compressor (Dunham-Bush model 1210NUF6V5KBJOC). R-507A was tested with a polyolester (CPI® Solest® 120); R-502 was tested with a mineral oil (Witco Suniso® 4GS) as a reference. The report summarizes the test conditions and provides a schematic of the test system. Three appendices present the tabular data, derived performance curves, and a plot comparing the relative efficiencies for R-507A to those with R-502. The tabular data for the tests include capacity, mass flow rate, compressor speed, current draw, input power, energy efficiency ratio (EER), coefficient of performance (COP), and relative COP (R-507A to R-502). The tests were performed at saturated suction temperatures of -40, -32, and -18 °C (-40, -25, and 0 °F) and saturated discharge temperatures of 35, 41, and 52 °C (95, 105, and 125 °F). Capacity, input power, and

COP are plotted for the same conditions. The resultant data for R-507A show 4-9% lower efficiency, depending on the suction and discharge temperatures. The relative COP appears to decrease with increasing discharge temperature. No source is indicated for the thermodynamic properties used.

R. R. Angers (Dunham-Bush, Incorporated), **Compressor Calorimeter Test of Refrigerant Blend R-125/143a/134a (44/52/4),** Alternative Refrigerants Evaluation Program (AREP) report 160, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, May 1994 (14 pages with 8 figures and 2 tables, available from JMC as RDB5660)

R-404A, twin-screw compressor

R. R. Angers (Dunham-Bush, Incorporated), **Compressor Calorimeter Test of Refrigerant Blend R-125/143a/134a (44/52/4),** Alternative Refrigerants Evaluation Program (AREP) report 122, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, October 1993 (14 pages with 8 figures and 2 tables, available from JMC as RDB3D22)

R-404A

R. R. Angers (Dunham-Bush, Incorporated), **Compressor Calorimeter Test of Refrigerant R-134a**, Alternative Refrigerants Evaluation Program (AREP) report 26, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, December 1992 (36 pages with 15 figures and 9 tables, available from JMC as RDB3826)

This report presents results of calorimeter (gas-cycle) testing for two refrigerants in a vertical, twin screw compressor (Dunham-Bush model 1212BHF6W4KBJOC). R-134a was tested with a polyolester (CPI® Solest® 120); R-22 was tested with a mineral oil (Witco Suniso® 4GS) as a reference. R-22 testing was performed using a 134 kW (100 HP) compressor motor, reduced to 107 kW (80 HP) for R-134a. The tests and resulting comparisons were repeated without and with vapor injection. The test conditions and a schematic of the test system are documented. Five appendices present the tabular data, a polynomial regression to them, derived performance curves, and a plot comparing the relative efficiencies with R-134a to those with R-22. The tabular data for the gas-cycle tests include capacity, mass flow rate, speed, current draw, input power, efficiency, and relative efficiency. The R-22 tests were performed at saturated suction temperatures of -7, -1, and 4 °C (20, 30, and 40 °F); those for R-134a were at -7, 2, and 10 °C (20, 35, and 50 °F). The saturated discharge temperature for both were 35, 41, and 46 °C (95, 105, and 115 °F). Capacity, input power, and COP are plotted for the same data ranges. The resultant data for R-134a show 13-17% lower efficiency, depending on the discharge temperature, without vapor injection and 4-10% lower with vapor injection at low suction temperatures. The efficiencies were similar to or as much as 10% higher at high suction temperatures. No source is indicated for the thermodynamic properties used, but the plots are noted as *based on preliminary data.*

R. R. Angers (Dunham-Bush, Incorporated), **Compressor Calorimeter Test of Refrigerant R-134a** Alternative Refrigerants Evaluation Program (AREP) report 31, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, December 1992 (22 pages with 8 figures and 5 tables, available from JMC as RDB3831)

This report presents results of calorimeter (gas-cycle) testing for two refrigerants in the same semihermetic, reciprocating piston compressor (Dunham-Bush model 201PHFOEMBJ6C). R-134a was tested with a polyolester (CPI® Solest® 32); R-22 was tested with a mineral oil (Witco Suniso® 4GS) for reference. The 27 kW (20 HP) compressor motor was replaced with a 15 kW (11 HP) motor for the R-134a tests. The test conditions and a schematic of the test system are documented. Three appendices present the tabular data, a polynomial regression to them, derived performance curves, and a plot of relative efficiencies (comparing the COP of R-134a to that of R-22). The tabular data for the gas-cycle tests include capacity, mass flow rate, speed, current draw, input power, efficiency, and relative efficiency at saturated suction temperatures of -12, 2, and 10 °C (10, 35, and 50 °F) and saturated discharge temperatures of 35, 41, 52, and 63 °C (95, 105, 125, and 145 °F). Capacity, input power, and COP are plotted for the same data ranges. The resultant data for R-134a show 2-6% lower efficiency, depending on the discharge temperature, at low suction temperatures and higher efficiency at high suction temperatures. No source is indicated for the thermodynamic properties used, but the plots are noted as *based on preliminary data.*

R. R. Angers (Dunham-Bush, Incorporated), **Compressor Calorimeter Test of Refrigerant R-717 (Ammonia)**, Alternative Refrigerants Evaluation Program (AREP) report 61, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, April 1993 (16 pages with 12 figures and 3 tables, available from JMC as RDB3C61)

This report presents results of calorimeter (gas-cycle) testing for R-717 (ammonia) in medium and large screw compressors. The actual tests were performed by Svenska Rotor Maskiner AB (SRM) in Sweden, using compressors with 127 and 204 mm (5 and 8") rotors. The report describes the test setup and shows it schemati-

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cally. Appendices present the test results including reference data with R-22. Saturated discharge temperature, saturated suction temperature, volumetric and adiabatic efficiency, brake horsepower, capacity, and coefficient of performance (COP) are tabulated for both compressors. The results show 8% lowered COP with R-717 at low suction temperatures improving to 5% better at high suction temperatures for the larger compressor size. The relative COP was 3-6% lower with R-717 in the smaller compressor. A second appendix indicates the lubricant content circulated, substantially higher with R-717. A third appendix provides 12 plots of the measured data including capacity, input power, and COP as functions of suction temperature for both refrigerants for both compressors.

R. E. Cawley (The Trane Company), **Compressor Calorimeter Test of Refrigerant R-134a**, Alternative Refrigerants Evaluation Program (AREP) report 18, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, February 1993 (12 pages with 7 figures and 2 tables, available from JMC as RDB-3818; table 1 contains type that is small and may be difficult to read)

C. Ellis (Lennox International, Incorporated), **Compressor Calorimeter and Drop-In Tests of Refrigerant R-290 (Propane),** Alternative Refrigerants Evaluation Program (AREP) report 3, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 23 September 1992 (48 pages with 5 figures and 7 tables, available from JMC as RDB3803)

This report summarizes a test of R-290 (propane) as an alternative to R-22 in unitary air-conditioners and heat pumps. It documents comparative performance; flammability and safety concerns are acknowledged and noted as separately addressed in other work. The report reviews the Alternative Refrigerants Evaluation Program (AREP) objectives and rationale for nomination of R-290 by Lennox International. The test procedure, instrumentation, and test equipment are described. The basic test machine used was a 10.6 kW cooling (3 ton) single-speed, medium-efficiency heat pump. Performance was measured with a standard scroll compressor (Copeland ZR34K1-PFV) for R-22 and with a second compressor, for R-290, with 14.5% greater volumetric displacement (Copeland ZRK40K1-PFV). The latter was specially prepared with motor thermocouples. Testing followed ASHRAE standards 37-1988 and 116-1989 and ARI standard 210/240. The lubricant used was a conventional white oil (Penreco Sontex 200LT); a solubility plot is presented for R-290 in mineral oil (Witco Suniso® 3GS). Measured increases in the heating and cooling capacities with R-290 are noted as resulting from the difference in compressors. System efficiencies were indicated as comparable, within ±2%. Appendices provide measured performance data and comparative plots of capacity, input power, efficiency, and efficiency ratio for evaporator temperatures of -18 to 16 °C (0-60 °F) and condenser temperatures of 32-60 °C (90-140 °F). Simulated and measured data are tabulated in both inch pound and metric (SI) units. The report concludes that performance with propane is predictable, despite small inconsistencies in thermodynamic data for it, that few equipment changes are needed to switch to R-290, and that retrofit may be possible. The report recommends that R-290 be further considered until another candidate becomes an "obvious choice" or ongoing safety evaluations and related efforts prove ineffective.

J. Gephart, E. B. Muir, P. Naculich, and S. G. Sundaresan (Copeland Corporation), **Compressor Calorimeter Test of Refrigerant Blends R-125/143a (45/55), R-125/143a/134a (44/52/4), and R-32/125/143a (10/45/45),** Alternative Refrigerants Evaluation Program (AREP) report 28, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, March 1993 (44 pages with 9 figures and 25 tables, available from JMC as RDB3828; available copy is difficult to read)

R-125/143a (45/55), R-404A, and R-32/125/143a (10/45/45)

D. S. Godwin (Air-Conditioning and Refrigeration Institute, ARI), **Alternative Refrigerants Evaluation Program (AREP) Compressor Calorimeter and System Drop-In Tests with R-22 Alternatives**, *Proceedings of the 45th Annual International Appliance Technical Conference* (University of Wisconsin, Madison, WI, 9-11 May 1994), IATC, Batavia, IL, 375-386, May 1994 (12 pages with 9 figures and 2 tables, available from JMC as RDB4554)

This paper summarizes results of calorimeter tests to measure performance of alternative refrigerants in compressors for air conditioners, heat pumps, and refrigeration equipment. It also addresses laboratory "drop-in" (unoptimized) tests in equipment. The tests were performed by companies participating in the Alternative Refrigerants Evaluation Program (AREP), established by the Air-Conditioning and Refrigeration Institute (ARI). The paper reviews the development of AREP and lists the 39 companies - in Europe, Japan, and North America - participating in this effort. It also lists the 14 candidate refrigerants selected for testing as potential replacements for R-22. They include R-134a; R-290 (propane); R-717 (ammonia); R-32/125 (60/40); R-32/134a (20/80), (25/75), (30/70), and (40/60); R-32/227ea (35/65); R-125/143a (45/55); R-32/125/134a (10/70/20) R-407B (24/16/60), and (30/10/60); and R-

32/125/290/134a (20/55/5/20). The candidates also include four for R-502, namely R-125/143a (45/55), R-32/125/134a (20/40/40) [R-407A]; R-125/143a/134a (10/45/45), and R-125/143a/134a (44/52/4) [R-404A]. The paper summarizes the results for R-32/125 (60/40); R-32/125/134a (30/10/60), R-32/134a (25/75), and R-32/134a (30/70). Four plots show the efficiencies and capacities measured in calorimeter tests relative to evaporating temperatures. Five additional plots, for the same candidates plus R-134a, map the efficiencies and capacities found in system "drop-in" tests as ratios to those for R-22. The paper concludes that several non-ozone depleting candidates offer performance approaching those of R-22. While most of the candidates resulted in a loss of capacity, efficiency, or both, some yielded improvements in either capacity or efficiency. The paper notes that efforts to standardize the test conditions led to good agreement in the calorimeter tests, but that higher scatter was found in the system tests. The cause is suggested as the result of differences in the specific equipment tested. The paper notes that performance is likely to improve with full optimization of the compressors and equipment for these fluids, but that such optimization is left to the individual companies. It also cites international cooperation as a significant and advantageous accomplishment.

D. S. Godwin and M. S. Menzer (Air-Conditioning and Refrigeration Institute, ARI), **Results of Compressor Calorimeter Tests in ARI's R-22 Alternative Refrigerants Evaluation Program,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC), Alliance for Responsible CFC Policy, Arlington, VA, 109-118, October 1993 (10 pages with 11 figures, available from JMC as RDB3A33)

D. S. Godwin and M. S. Menzer (Air-Conditioning and Refrigeration Institute, ARI), **Results of Compressor Calorimeter Tests in ARI's R-22 Alternative Refrigerants Evaluation Program,** *R-22 and R-502 Alternatives* (Proceedings of the ASHRAE/-NIST Refrigerants Conference, Gaithersburg, MD, 19-20 August 1993), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1-18, 1994 (18 pages with 12 figures and 14 tables; 25 page preprint available from JMC as RDB3862)

This paper summarizes results of calorimeter tests to measure performance of alternative refrigerants in compressors for air conditioners, heat pumps, and refrigeration equipment. The tests were performed by companies participating in the Alternative Refrigerants Evaluation Program (AREP) established by the Air-Conditioning and Refrigeration Institute (ARI). The paper reviews the development of AREP and lists the 39 companies participating in this international effort. It also lists the 14 candidate refrigerants selected for testing as potential replacements for R-22. They include R-134a; R-290 (propane); R-717 (ammonia) R-32/125 (60/40); R-32/134a (20/80), (25/75), (30/70), and (40/60); R-32/227ea (35/65); R-125/143a (45/55); R-32/125/134a (10/70/20) [R-407B], (24/16/60), and (30/10/60); and R-32/125/290/134a (20/55/5/20). The candidates also include four for R-502, namely R-125/143a (45/55), R-32/125/134a (20/40/40) [R-407A]; R-125/143a/134a (10/45/45), and R-125/143a/134a (44/52/4) [R-404A]. The paper briefly outlines three facets of the program, including calorimeter, drop-in, and heat transfer testing. The test conditions and reporting requirements for the compressor calorimeter tests are outlined. The measured capacities and efficiencies are tabulated as ratios to those for the reference (R-22 and R-502) fluids for 12 of the candidates. The results also are plotted relative to the evaporating temperatures of the tests, accompanied by an explanation of the data and variances. The paper concludes that several non-ozone depleting candidates offer performance approaching those of R-22 and R-502, and some offer better capacity and/or efficiency. Moreover, performance is likely to improve with full optimization of the compressors for these fluids.

M. Hayano and T. Kobuna (Toshiba Corporation, Japan), **Calorimeter Test of Rotary Compressors with HFC-Blend Refrigerants,** paper 6.1, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 135-138, December 1994 (4 pages with 12 figures and 1 table; in Japanese with abstract, figures, and table in English; RDB5425)

R-22, R-407C, R-410A, two-cylinder rotary rolling-piston compressor

K. E. Hickman (York International Corporation), **Compressor Calorimeter Test of Refrigerant R-134a,** Alternative Refrigerants Evaluation Program (AREP) report 1, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, September 1992 (10 pages with 6 figures, available from JMC as RDB-3801)

This report provides summary plots based on calorimeter test results for a large semihermetic (accessible hermetic), reciprocating piston compressor. The plots present capacity and input

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power multipliers, for converting from R-22 to R-134a, as functions of saturated suction and discharge temperatures. One set of figures for operation at 1750 rpm shows the effect on performance of retaining the same motor for both refrigerants, namely oversizing the motor for R-134a. The second set shows the benefits of changing the motor to suit the reduced power requirements with R-134a, by changing the speed from 1750 to 1775 rpm. Modelled compressor data, based on measurements for a single 9.53 cm (3.75") bore and 7.87 cm (3.10") stroke, are presented. The results cover -29 to 21 °C (-20 to 70 °F) saturated suction and 27-68 °C (80-155 °F) saturated discharge conditions.

K. Hossner and H. Renz (Bitzer Kühlmaschinenbau GmbH, Germany), **Compressor Calorimeter Test of Refrigerant R-134a**, Alternative Refrigerants Evaluation Program (AREP) report 15, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, March 1993 (10 pages with 6 figures and 2 tables, available from JMC as RDB3815)

T. Iizuka and A. Ishiyama (Hitachi Limited, Japan), **Reliability of Compressors for HFC-Based Refrigerants,** paper 6.2, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 139-144, December 1994 (6 pages with 15 figures and 7 tables; in Japanese with abstract, figures, and tables in English; RDB5426)

R-22, R-32, R-125, R-134a, R-32/134a (50/50) and (30/70), and R-407C; polyolester and carbonate lubricants, compatibility

N. Kanzaki (Kobe Steel, Limited, Japan), **Compressor Calorimeter Test of Refrigerant R-134a**, Alternative Refrigerants Evaluation Program (AREP) report 43, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1993 (10 pages with 3 tables, available from JMC as RDB3843)

performance test for R-134a

S. Komatsu (Sanden Corporation, Japan), **Compressor Calorimeter Test of Refrigerant Blend R-125/143a**, Alternative Refrigerants Evaluation Program (AREP) report 147, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1994 (8 pages with 3 figures and 2 tables, available from JMC as RDB5647)

This report summarizes performance measurements of R-404A [R-125/143a/134a (44/52/4)] with an unidentified ester lubricant in a rotary, rolling-piston compressor. Note that the title disagrees with the report on the refrigerant tested.

J. W. Linton, W. K. Snelson, P. F. Hearty, A. R. Triebe (National Research Council, Canada, NRCC) F. T. Murphy, R. E. Low (ICI Klea, UK), and B. E. Gilbert (ICI Klea, USA), **Comparison of R-407C and R-410A with R-22 in a 10.5 kW (3.0 TR) Residential Central Heat Pump**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 1-6, July 1996; republished in German as **Vergleich von R407C und R410A mit R22 in einer Zentral-klimaanlage für Wohnhäuser mit 10,5 kW Leistung,** *Die Kälte- und Klimatechnik,* Germany, 49(2):74-82, February 1996 (6/9 pages with 4 figures and 2 tables, RDB6746)

performance comparison for both heating and cooling with partial optimization, concludes that capacities with R-407C and R-410A were 91-101% and 98-107%, respectively of that with R-22 depending on the operating conditions and modifications to the indoor heat exchanger

K. W. Mumpower (Bristol Compressors, Incorporated) and M. B. Shiflett (DuPont Fluoroproducts), **Calorimeter Experiments with Suva® AC9000,** *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 61-66, July 1994 (6 pages with 6 figures and 1 table, RDB4811)

R-407C [R-32/125/134a (23/25/52)]

K. W. Mumpower (Bristol Compressors, Incorporated), **Compressor Calorimeter Test of Refrigerant Blend R-32/125/134a (10/70/20)**, Alternative Refrigerants Evaluation Program (AREP) report 4, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, March 1993 (44 pages with 5 figures and 23 tables, available from JMC as RDB3804)

This report summarizes calorimeter test data for R-22 and R-407B [R-32/125/134a (10/70/20)] for a hermetic, reciprocating piston compressor (Bristol Inertia® model H25A353CBC). Performance tables, calculated with thermodynamic data supplied by the refrigerant manufacturer, and a revision, based on data from NIST REFPROP 3x, are provided; the latter indicate increased capacity over the former. Raw and regressed performance (capacity, power, current, mass flow, and efficiency) tables are provided for -7 to 13 °C (-20 to 55 °F) evaporating and 27-66 °C (80-150 °F) condensing temperatures, based on 8 °C (15 °F) subcooling and 11 °C (20 °F) superheat. Plots compare the capacity and efficiency of the blend versus R-22. A performance plot depicts the motor characteristics and small shift in the torque range required (and corresponding efficiencies) for the two refrigerants. A table summarizes the blend pressures at test temperatures. Tests were performed with mineral oil (Witco Suniso® 3GS). The test conditions and instrumentation accuracy are indicated. The report concludes that the blend yielded significantly higher capacities at condensing temperatures below 54 °C (130 °F), but lower capacities at higher temperatures. Similarly, the blend was less efficient than R-22 except at condenser temperatures below 38 °C (100 °F).

K. Mumpower (Bristol Compressors, Incorporated), **Compressor Calorimeter Test of Refrigerant R-290**, Alternative Refrigerants Evaluation Program (AREP) report 21, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, March 1993 (30 pages with 5 figures and 11 tables, available from JMC as RDB3821)

K. Mumpower (Bristol Compressors, Incorporated), **Compressor Calorimeter Test of Refrigerant Blend R-125/143a/134a (44/52/4)**, Alternative Refrigerants Evaluation Program (AREP) report 55, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, March 1993 (32 pages with 4 figures and 13 tables, available from JMC as RDB3855)

R-404A

N. Murata (Mitsubishi Heavy Industries, Limited, Japan), **Compressor Calorimeter Test of Refrigerant Blend R-125/143a/134a (44/52/4)**, Alternative Refrigerants Evaluation Program (AREP) report 115, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, October 1993 (8 pages with 2 figures and 2 tables, available from JMC as RDB3D15)

R-404A

H. Namiki (Mayekawa Manufacturing Company, Limited, Japan), **Compressor Calorimeter Test of Refrigerant R-134a**, Alternative Refrigerants Evaluation Program (AREP) report 145, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1994 (8 pages with 3 figures and 2 tables, available from JMC as RDB4745)

This report summarizes performance measurements of R-134a with an unidentified mineral oil in a reciprocating piston compressor. The test rig is shown schematically. Two tables present evaporating and condensing temperatures and pressures. They also give the capacity, input power, and coefficient of performance (COP) normalized to those with R-22 at corresponding conditions. Measurements were made for -21, -9, and 8 °C (-6, 16, and 46 °F) evaporating and 33, 43, 53, and 57 °C (91, 109, 127, and 135 °F) condensing. Two plots show the dependence of the normalized COPs on the evaporating and condensing temperatures. The COPs decreased by 5-15% with R-134a, and were most sensitive to decreasing evaporating temperature.

H. Namiki (Mayekawa Manufacturing Company, Limited, Japan), **Compressor Calorimeter Test of Refrigerant R-134a,** Alternative Refrigerants Evaluation Program (AREP) report 79, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, May 1993 (10 pages with 3 figures and 3 tables, available from JMC as RDB3C79)

This report summarizes performance measurements of a twin-screw compressor with R-134a and an unidentified polyolester lubricant. The test rig is shown schematically. Two tables present evaporating and condensing temperatures and pressures. They also give the capacity, input power, and coefficient of performance (COP) normalized to those with R-22 at corresponding conditions. Measurements were made for -15, -5, 0, and 7 °C (5, 23, 32, and 45 °F) evaporating and 35 and 45 °C (95 and 113 °F) condensing. Two plots show the dependence of the normalized COPs on the evaporating and condensing temperatures. The COPs decreased by 10% at low evaporating temperatures, but increased by up to 10% at high evaporating temperatures. The decreased slightly with increasing condensing temperature.

T. Nitta (Mitsubishi Heavy Industries, Limited, Japan), **Compressor Calorimeter Test of Refrigerant R-125/143a/134a (44/52/4)**, Alternative Refrigerants Evaluation Program (AREP) report 141, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1994 (6 pages with 2 figures and 1 table, available from JMC as RDB4741)

R-404A, ester lubricant, rotary rolling-piston compressor

K. S. Sanvordenker (Tecumseh Products Company), **Compressor Calorimeter Test of Refrigerant Blend R-32/125/134a (23/25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 181, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, August 1994 (14 pages with 4 figures and 4 tables, available from JMC as RDB5681)

This report compares the performance of R-407C to that with R-22 and that with R-32/125/134a (30/10/60) in an 8.8 kW (2½ ton) hermetic, reciprocating piston compressor (Tecumseh AW5530G). A polyolester (POE) lubricant (Mobil EAL Arctic® 32) was used for these tests, which were performed using secondary refrigerant calorimetry. The report summarizes the evaluation purpose and experimental details. Two tables show the calorimeter parameters for

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representative evaporator and condenser test conditions. Two additional tables compare the measured capacity and efficiency of R-407C to those of R-22 and R-32/125/134a (30/10/60). Four plots show the capacity and energy-efficiency ratios for the same comparisons as functions of the evaporator and condensing temperatures, for ranges of -12 to 13 °C (10-55 °F) and 32-54 °C (90-130 °F) respectively. The report concludes that R-407C and R-22 have identical capacities at 7 °C (45 °F) evaporating and 54 °C (130 °F) condensing, but that R-407C is more favorable at lower condensing temperatures. Further, R-407C offers marginally lower performance compared to R-32/125/134a (30/10/60), but the differences are within the range of experimental uncertainty. It recommends further evaluation of R-407C based on its nonflammability compared to the other blend formulation.

N. Sawada (Sanyo Electric Company, Limited, Japan), **Compressor Calorimeter Test of Refrigerant Blend R-32/125/134a (23/25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 143, Air-Conditioning and Refrigeration Institute (ARI), Arlington VA, January 1994 (12 pages with 5 figures and 1 table, available from JMC as RDB4743)

R-407C, polyolester lubricant, rotary rolling-piston compressor

M. B. Shiflett and A. Yokozeki (DuPont Fluoroproducts), **Compressor Calorimeter Experiments on R-502 and R-22 Alternatives**, *Proceedings of the 1994 International Refrigeration Conference at Purdue,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 401-406, July 1994 (6 pages with 7 figures, RDB4853)

R-404A [R-125/143a/134a (44/52/4)], R-407C (R-32/125/134a (23/25/52)]

K. Tojyo (Mitsubishi Electric Corporation, Japan), **Compressor Calorimeter Test of Refrigerant Blend R-125/143a/134a (44/52/4)**, Alternative Refrigerants Evaluation Program (AREP) report 78, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1993 (6 pages with 1 figure and 2 tables, available from JMC as RDB3C78)

R-404A

Y. Seyama (Sanyo Electric Company, Limited, Japan), **Compressor Calorimeter Test of Refrigerant Blend R-125/143a/134a (44/52/4)**, Alternative Refrigerants Evaluation Program (AREP) report 171, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, March 1994 (10 pages with 3 figures and 1 table, available from JMC as RDB5671)

R-404A with an unidentified ester lubricant compared to R-22 in a reciprocating piston compressor

J. P. Soley (Unidad Hermética, S.A., Spain), **Compressor Calorimeter Test of Refrigerant Blend R-125/143a/134a (45/52/4),** Alternative Refrigerants Evaluation Program (AREP) report 158, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, February 1994 (8 pages with 2 figures and 1 table, available from JMC as RDB5658)

This report compares the measured performance of R-404A and an unidentified polyolester (POE) lubricant to that of R-502 and mineral oil. The tests were made with a reciprocating-piston compressor (Unidad Hermética model MR22FB). The document lists the compressor characteristics and presents the test conditions and results in a table. Plots show the performance with R-404A and R-502. The capacity was approximately 4% lower with R-404A at the lowest evaporator temperature, -40 °C (-40 °F), but increased to 10% higher at -10 °C (14 °F). The efficiency was lower by 9 and 7% at the same two points for condensing at 55 °C (131 °F).

K. Tojo (Hitachi, Limited, Japan), **Compressor Calorimeter Test of Refrigerant R-125/143a/134a (44/52/4)**, Alternative Refrigerants Evaluation Program (AREP) report 140, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1994 (6 pages with 2 figures and 1 table, available from JMC as RDB4740)

R-404A, scroll compressor

K. Tojo (Hitachi, Limited, Japan), **Compressor Calorimeter Test of Refrigerant R-32/125/134a (23/25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 153, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1994 (8 pages with 2 figures and 1 table, available from JMC as RDB4753)

R-407C with an unidentified polyolester lubricant, rotary rolling-piston compressor

H. Wakabayashi (Matsushita Electric Industrial Company, Limited, Japan), **Compressor Calorimeter Test of Refrigerant Blend R-32/125/134a (23/25/53)**, Alternative Refrigerants Evaluation Program (AREP) report 144, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1994 (10 pages with 4 figures and 2 tables, available from JMC as RDB4744)

R-407C, rotary, rolling-piston compressor

E. Wobst and H. Friedrich (Institut für Luft- und Kältetechnik Dresden, ILK, Germany), **Ermittlung der Leistungsparameter von Zwei Scroll Verdichtern** [Determination of the Capacity Parameters of Two

Scroll Compressors], Solvay Fluor und Derivate GmbH, Hannover, Germany, 1999 (in German, RDB9848)

compressor tests with R-22, R-134a, R-290 (propane), R-407C, and R-410A [summarized in RDB9845]

H. Yasuda (Hitachi, Limited, Japan), **Compressor Calorimeter Test of Refrigerant R-134a**, Alternative Refrigerants Evaluation Program (AREP) report 57, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1993 (6 pages with 2 figures and 1 table, available from JMC as RDB3C57)

This report summarizes calorimeter tests of R-134a in a 1-10 kW (0.3-2.8 ton) rotary, rolling-piston compressor using an unidentified polyolester (POE) lubricant. The charge and lubricant quantities, motor characteristics, and test conditions are indicated. A table presents evaporator and condenser temperatures and pressures along with compressor speed and discharge temperature. The capacity, input, and efficiency are tabulated relative to performance with R-22. Plots compare the coefficient of performance (COP) and capacity ratio at 46 °C (115 °F) for compressor speeds of 2000-6000 rpm and for evaporating temperatures of 5.5-11 °C (42-52 °F). The efficiency and capacity are indicated to be approximately 5-8% and 32-38% lower, respectively.

Drop-In Tests

A. Bangheri, **Wärmepumpen Erfahrungsbericht mit dem neuen Arbeitsmittel R410A** [Heat Pump Trials with the New Working Fluid R-410A], Firma Heliotherm Solartechnik, Kirchberg, Austria, August 1996 (in German, rdb8C09)

performance tests, long-term comparisons between R-22 and R-410A

M. Barreau, P. Weiss, and P. Fauvarque (Elf Atochem S.A., France), **Field Testing Using HCFC-22 Replacements**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 21-30, October 1995 (10 pages with 5 figures and 2 tables, available from JMC as RDB5A42)

R-22, R-407C, R-23/32/134a (4.5/21.5/74) [FX-220], laboratory performance tests

A. Bensafi and M. Mondot (Centre Technique des Industries Aérauliques et Thermiques, CETIAT), France), **Evaluation expérimentale des mélanges HFC** [Experimental Evaluation of HFC Blends], *Revue Pratique du Froid*, (847):, June 1997 (rdb-9316)

performance comparison

J. Berge, S. L Kwon, and L. Naley (Thermo King Corporation), **Drop-In Test of Refrigerant Blends R-125/143a (45/55) and R-125/143a (50/50)**, Alternative Refrigerants Evaluation Program (AREP) report 156, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1994 (14 pages with 8 figures and 10 tables, available from JMC as RDB4756)

R-125/143a (45/55) and R-507A [R-125/143a (50/50)] with an unidentified polyolester compared to R-502 with an unidentified alkylbenzene and with an unidentified polyolester in a transport refrigeration unit with a reciprocating piston compressor

J. Berge, S. L. Kwon, and L. Naley (Thermo King Corporation), **Drop-In Test of Refrigerant Blends R-32/125/143a (10/45/45) and R-32/125/134a (20/40/40)**, Alternative Refrigerants Evaluation Program (AREP) report 87, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1993 (8 pages with 4 figures and 2 tables, available from JMC as RDB3C87)

R-32/125/143a (10/45/45) and R-407A

J. Berge, S. L. Kwon, and L. Naley (Thermo King Corporation), **Drop-In Test of Refrigerant Blends R-125/143a/134a (44/52/4) and R-125/143a (45/55)**, Alternative Refrigerants Evaluation Program (AREP) report 51, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1993 (12 pages with 4 figures and 5 tables, available from JMC as RDB3851)

R-404A and R-125/143a (45/55)

D. Clodic (École des Mines de Paris, France), **Comparison of Performance between R404A and AZ50 Used in Commercial Refrigeration**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 73-78, July 1994 (6 pages with 1 figure and 2 tables, RDB4813)

R-404A [R-125/143a/134a (44/52/4)], R-507A [R-125/143a (50/50), AZ-50], R-502

S. Devotta, M. M. Kulkarni, and M. Lele (National Chemical Laboratory, India), **Performance of Refrigerators Retrofitted with HFC-134a and HC blend**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Re-

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sponsible Atmospheric Policy, Arlington, VA, 66-73, November 1997 (8 pages with 2 tables, RDB8328)

comparative performance tests of R-134a with a polyolester (POE) lubricant and the hydrocarbon (HC) blend R-290/600a (50/50) [propane/-isobutane] with a mineral oil: describes drop in tests under laboratory conditions of the cited refrigerants and comparative tests with R-12; describes the retrofit procedures; tabulates results for energy consumption, no-load pull down, and ice making tests; concludes that better evacuation, leak testing, and charging practices are needed; also concludes that the performance of R-134a and R-290/600a would be similar in optimized systems, but that the HC blend is preferred based on ozone depletion and global warming issues, but that safety issues need to be investigated

ETL Testing Laboratory, Incorporated, **Drop-In Test of Refrigerant R-290 (Propane)**, Alternative Refrigerants Evaluation Program (AREP) report 33, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, December 1992 (28 pages with 17 tables, available from JMC as RDB3833)

K. Furuhama (Toshiba Corporation, Japan), **Drop-in Test of Refrigerant Blend R-32/125/134a (23/-25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 172, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1994 (16 pages with 4 figures and 7 tables, available from JMC as RDB5672)

R-407C with an unidentified ester lubricant compared to R-22 with mineral oil in an air-to-air, multicoil heat pump using an adjustable-speed rotary, rolling piston compressor in both the cooling and heating modes; composition shift

D. S. Godwin, **Results of System Drop-In Tests in ARI's R-22 Alternative Refrigerants Evaluation Program**, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1 December 1993 (10 pages with 7 figures and 2 tables, available from JMC as RDB4868)

V. Havelsky and P. Tomlein (Slovak Technical University, Slovakia), **Experimental Investigation of R12 Working Fluid Replacements**, *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 78-84, 1997 (7 pages with 3 figures and 2 tables, RDB9314)

drop-in, laboratory performance (capacity and efficiency) tests of R-12, R-22, R-401A, R-409A, R-12/134a (50/50 (identified in the paper as "ZM1"), and R-12/134a (20/80) (identified in the paper as "ZM2") in an 8.3 kW (2.4 ton) air-cooled milk chiller; paper also summarizes total equivalent warming impact (TEWI) analyses for the systems using these refrigerants; discusses considerations for retrofit; concludes that R-134a is the only suitable replacement subject to use of alkylbenzene (AB) lubricant; also concludes that it still is possible to operate older equipment with a small expense for conversion and indicates that R-401A and R-409A may have roles as service fluids

P. F. Hearty, J. W. Linton, A. R. Triebe, W. K. Snelson (National Research Council, Canada, NRCC), **Performance Comparison of R-502 Replacements in a Commercial Scale Low Temperature Refrigeration Plant with a Two Stage Compressor,** *Proceedings of the 1996 International Refrig*eration *Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 51-56, July 1996 (6 pages with 4 figures and 1 table, RDB6757)

R-404A, R-407A, R-507A

P. F. Hearty, J. W. Linton, W. K. Snelson, and A. R. Triebe (National Research Council, Canada, NRCC), **Drop-In Test of Refrigerant Blend R-125/143a/134a (44/52/4),** Alternative Refrigerants Evaluation Program (AREP) report 52, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 25 February 1993 (18 pages with 4 figures and 4 tables, available from JMC as RDB3852)

R-404A and R-502

F. Hill (Dunham-Bush, Incorporated), **Drop-In Test of Refrigerant R-134a**, Alternative Refrigerants Evaluation Program (AREP) report 50, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1993 (6 pages, available from JMC as RDB3850)

This report summarizes a performance test of R-134a in a water-cooled chiller (Dunham-Bush model WCFX20), to compare capacity and efficiency to those with R-22 for a drop-in (no components changed) substitution. This chiller employs two twin screw compressors (Dunham-Bush model 1210BHF6W4JBJ0C), a flooded evaporator with interior and exterior tube enhancement, and a shell-and-tube condenser with integral-finned tubes. R-22 was tested with an unidentified mineral oil as a reference; R-134a was tested with a lubricant containing 85% unidentified ISO 150 polyolester and 15% mineral oil. The mineral oil content in the latter was residual from the first test. A table compares entering and leaving water temperatures and flow rates in the heat exchangers, capacity, input power, approach temperatures, subcooling and superheat. The report notes that the capacity and input power with R-134a were 68.0 and 68.4%, respectively, of those with R-22. The efficiency was, therefore, unchanged within the instrumentation accuracy. Oil return and evaporator performance were both satisfactory in the R-134a test despite the residual mineral oil.

H. Kanno (Mitsubishi Heavy Industries, Limited, Japan), **Drop-In Test of Refrigerant Blend R-125/143a**, Alternative Refrigerants Evaluation Program (AREP) report 47 Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, April 1993 (20 pages with 6 figures and 9 tables, available from JMC as RDB3847)

N. Kanzaki (Kobe Steel, Limited, Japan), **Drop-In Test of Refrigerant R-134a,** Alternative Refrigerants Evaluation Program (AREP) report 109, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, September 1993 (4 pages with 2 tables, available from JMC as RDB3D09)

This report summarizes a performance test of R-134a in a 40 hp, 207 kW (59 ton), water-cooled chiller with a twin-screw compressor and shell-and-tube heat exchangers. The results are tabulated for R-134a along with corresponding data for R-22. Both refrigerants were tested with an unidentified polyolester lubricant. The charge and lubricant quantities and the test conditions are indicated. Operating temperatures and pressures are given for the inlets and outlets of the compressor, condenser, expansion device, and evaporator. The results show decreases of 34.3 and 29.0% in capacity and increases of 2.1 and 5.1% in efficiency, with and without an economizer, compared to R-22.

H. Kasahara, M. Nakamura, and S. Watabe (Mitsubishi Heavy Industries, Limited, Japan), **Packaged Air Conditioner with a Refrigerant Mixture of R-32/125/134a**, paper 2.4, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 33-37, December 1994 (5 pages with 5 figures and 4 tables; in Japanese with abstract, figures, and tables in English; RDB5407)

R-32/125/134a (30/10/60) and (23/25/52) [R-407C]

M. Katayama (Fujitsu General Limited, Japan), **Drop-In Test of Refrigerant Blend R-32/125/134a (23/25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 170, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, May 1994 (16 pages with 9 figures and 2 tables, available from JMC as RDB5670)

R-407C with an polyolester lubricant (JS4156A1) compared to R-22 with mineral oil (Witco Suniso® 4GSD) in a room heat pump, with and adjustable-speed rotary, rolling-piston compressor, in both the cooling and heating modes

S. Komatsu (Sanden Corporation, Japan), **Drop-in Test of Refrigerant Blend R-125/143a/134a (44/52/4),** Alternative Refrigerants Evaluation Program (AREP) report 173, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1994 (10 pages with 5 figures and 1 table, available from JMC as RDB5673)

This report compares performance measurements of R-404A with an unidentified ester lubricant to those for R-502 with mineral oil in a chest freezer using a rotary, rolling-piston compressor.

S. N. Kondepudi (Electric Power Research Institute, EPRI), **Drop-In Testing of R-32 Blends as R-22 Alternatives in a Split-System Air Conditioner,** paper DE-93-9-2 (3733), *Transactions* (Annual Meeting, Denver, CO, June 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(2):406-413, 1993 (8 pages with 2 figures and 8 tables, RDB3621)

This paper summarizes capacity and efficiency tests of five zeotropic blends in a 2 ton, split-system air conditioner. The refrigerants included three mixtures of R-32 and R-134a, with 20, 30, and 40% R-32 by mass, and two of R-32 and R-152a, with 30 and 40% R-32. The five blends were selected as candidate R-22 replacements based on prior studies. Testing was performed by an independent testing laboratories, and confirmed by separate tests by the manufacturer of the air conditioner; both were performed in accordance with standard rating test procedures. The fluids were tested under near "drop-in" conditions, without equipment modification except for substitution of a manual expansion device and replacement of the refrigerant and lubricant. An unidentified polyolester lubricant was used. The paper summarizes the need for R-22 alternatives, candidates identified in prior and ongoing studies, testing and equipment details, and measured results. It also compares the findings to simulations. Measured capacity and efficiency fell below simulated results, but the test system had not been optimized for the alternative refrigerants. The blends tested generally showed steady-state efficiency to be within 2% of that of R-22, but offered lower capacity. R-32/134a (40/60) was identified as a promising retrofit fluid since it yielded steady state efficiency and capacity 1% higher than R-22, though the seasonal performance (SEER) was 1% lower. The paper con-

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cludes with recommendations to better evaluate the refrigerant blends tested.

M. Kurachi (Matsushita Refrigeration Company, Japan), **Drop-In Test of Refrigerant Blend R-32/-125/134a (23/25/52),** Alternative Refrigerants Evaluation Program (AREP) report 169, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, May 1994 (14 pages with 12 figures and 3 tables, available from JMC as RDB5669)

R-407C with an unidentified polyolester (POE) lubricant compared to R-22 with mineral oil in an air-to-air, multicoil heat pump using a scroll compressor in both the cooling and heating modes; internal composition change

M. Lindsay and D. Shapiro (Hussmann Corporation), **Drop-In Test of Refrigerant Blend R-125/-143a/134a (44/52/4),** Alternative Refrigerants Evaluation Program (AREP) report 58, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, February 1993 (8 pages with 3 figures and 1 table, available from JMC as RDB3C58)

This report summarizes drop-in testing of R-404A in a low- and two medium-temperature display cases (Hussmann G6FA129 and FHMG12U, respectively). They were tested with an indoor condensing unit, including a Copeland Discus (reciprocating semi-hermetic) compressor, and an air-cooled condenser. The lubricant used both for the R-404A and R-502 reference tests was Mobil EAL Arctic® 22. The test setup is described and shown schematically. The results are tabulated and plotted both for medium- and low-temperature display cases. The relative power use was 10% higher with R-404A at 35 °C (95 °F) outdoor temperature, but nearly the same or 4% lower at 10 °C (50 °F). Comparative run time data also are provided.

J. W. Linton, W. K. Snelson, P. F. Hearty, A. R. Triebe (National Research Council, Canada, NRCC), **Performance Comparison of R-22 with R-407C in a Residential Size Central Air Conditioner**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:893-897, 1995 (5 pages with 2 figures and 1 table, rdb7926)

laboratory performance test of a 10.5 kW (3 ton), split-system, air-to-air air conditioner retrofit from R-22 with alkylbenzene to R-407C with a polyolester (POE) lubricant

J. W. Linton, W. K. Snelson, A. R. Triebe, and P. F. Hearty (National Research Council, Canada, NRCC), **Some Performance Measurements of Four Long Term Replacements in a Test Facility Containing a Scroll Compressor**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:898-905, 1995 (8 pages with 8 figures and 3 tables, RDB7928)

R-404A [R-125/143a/134a (44/52/4)], R-407A [R-32/125/134a (20/40/40)], R-407B [R-32/125/134a (10/70/20)], R-507A [R-125/143a (50/50)]

J. W. Linton, W. K. Snelson, A. R. Triebe, and P. F. Hearty (National Research Council, Canada, NRCC), **System Performance of Some Long Term R-502 Replacements**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 383-388, July 1994 (6 pages with 8 figures and 2 tables, RDB4850)

R-404A [R-125/143a/134a (44/52/4)], R-407A [R-32/125/134a (20/40/40)], R-407B [R-32/-125/134a (10/70/20)], R-507A [R-125/143a (50/50)]

B. Y. Liu, M-L. Tomasek, and R. K. Radermacher (University of Maryland), **Experimental Results with Hydrocarbon Mixtures in Domestic Refrigerator/Freezers**, paper CH-95-24-1, *Transactions* (Winter Meeting, Chicago, IL, 28 January - 1 February 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(1):1415-1421, 1995 (7 pages with 6 figures and 1 table, RDB5244)

R-12, R-290/600 (70/30)

T. Nitta (Mitsubishi Heavy Industries, Limited, Japan), **Drop-In Test of Refrigerant R-32/125/134a (23/25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 136, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1994 (8 pages with 1 figure and 4 tables, available from JMC as RDB4736)

This report summarizes performance measurements of R-407C, with an unidentified ester lubricant, in a 2.4 kW (8300 Btu/hr) split-system room air conditioner (RAC) / heat pump with a scroll compressor. The results are compared to corresponding data for R-22 with alkylbenzene. A schematic illustrates the refrigerant circuit. The data for the cooling and heating modes are summarized in two tables. The charge and lubricant quantities are indicated. Operating temperatures and pressures are given for the inlets and outlets of the compressor, condenser, expansion device, and evaporator. The results show decreases of 7 and 1 % in the cooling and heating modes, respectively, with corresponding decreases in the coefficient of performance (COP) of 13 and 12%. The report notes that the discharge pressure with R-407C is 6-13% higher than with R-22, but the discharge temperature is 0.5-3 °C (0.9-5.4 °F) lower.

M. Paulus-Lanckriet and O. Buyle (Solvay Research and Technology, Belgium), **R407C/R410A: An Analysis of the Two Prominent Candidates for Replacement of R22 in Refrigeration Applications,** *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 85-93, 1997 (9 pages with 12 figures and 1 table, RDB9315)

compares the properties and performance of R-22, R-407C, and R-410A, the first tested with an alkylbenzene (AB) lubricant and last two with a polyolester (POE) lubricant (Mobil EAL Arctic® 32) in a laboratory test loop; concludes that the volumetric capacity of R-410A exceeds those of the other two refrigerants and that the efficiency of R-410A exceeds that of R-407C without optimization for either

M. B. Shiflett (DuPont Fluoroproducts), **HCFC-22 Alternatives for Air Conditioners and Heat Pumps**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 1-6, July 1994 (6 pages with 5 figures, available from JMC as RDB4801)

This paper discusses alternative refrigerants for R-22 in unitary air conditioners and heat pumps, with emphasis on R-407C - R-32/125/134a (23/25/52). The paper notes that while R-134a and R-410A also were in the focus of interest in the Alternative Refrigerants Evaluation Program (AREP), both would require system redesign due to capacity and efficiency differences with R-22. R-407C is suggested as offering the closest performance match to R-22 in existing equipment. The paper notes that R-407C was formulated for similar capacity, highest efficiency, and to be nonflammable under both normal and abnormal operating conditions. The paper then outlines tests of R-407C in an 8.8 kW (2½ ton), air-to-air, split-system heat pump. The paper describes and schematically shows the instrumentation; it also outlines the test procedures. The results are presented and compared for both R-22 and R-407C, with the same reciprocating piston compressor and an unidentified polyolester lubricant. A series of four plots compare capacity, efficiency, compressor discharge temperature and pressure for cooling at 28 and 35 °C (82 and 95 °F) and heating at -8 and 8 °C (17 and 47 °F). The paper also discusses system modifications to improve the capacity and efficiency, including use of a suction line accumulator to allow composition shifting for improved heating capacity. Estimated improvements are discussed with counterflow heat exchangers and a liquid-suction heat exchanger. The paper concludes that R-407C offers similar heating and cooling capacity to R-22 with a 3-4% loss in efficiency. Gains of up to 6% in heating capacity or 8-10% in cooling efficiency and capacity are suggested for optimized systems. DuPont's product name for R-407C is Suva® AC9000.

C. N. Shores and H. B. Ginder (York International Corporation), **Drop-In Test of Refrigerant R-134a**, Alternative Refrigerants Evaluation Program (AREP) report 89, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1993 (4 pages with 2 tables, available from JMC as RDB3C89)

This report summarizes "drop-in" performance tests of R-134a in a water-cooled, centrifugal chiller with a nominal capacity of 3.2 MW (900 tons) for R-22. The report describes the test equipment and conditions. The entering and leaving water temperatures, flow rates, refrigerant pressures and subcooling are tabulated along with comparative R-22 measurements. A second table gives the capacity, input power, and specific power (reciprocal of efficiency) for R-134a normalized to those for R-22. The report concludes that the chiller capacity and efficiency dropped by 30% and 4.5% respectively when run with R-134a. The report discusses these decreases, attributing them to differences in both thermodynamic properties and the operating point in the compressor performance map. R-22 was tested with a mineral oil and R-134a with a polyolester, both unidentified. The impeller speed was held constant between the two refrigerants.

H. W. Sibley (Carrier Corporation), **Drop-In Tests of Refrigerant Blends R-32/125/134a (30/10/60), R-32/125/134a (25/20/55), and R-32/125/134a (23/25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 178, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1994 (12 pages with 2 figures and 6 tables, available from JMC as RDB5678)

R-32/125/134a (30/10/60), (25/20/55), and (23/25/52) [R-407C] with a polyolester (POE) lubricant (Mobil EAL Arctic® 32) compared to R-22 with an alkylbenzene (AB) lubricant (Shrieve Zerol® 150) in a 0.9 kW (8000 Btu/hr) window air conditioner (Carrier 51AGA108111) using a hermetic, rotary rolling-piston compressor

H. W. Sibley (Carrier Corporation), **Drop-In Tests of Refrigerant Blends R-32/125/134a (30/10/60) and R-32/125/134a (23/25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 179,

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Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1994 (16 pages with 4 figures and 8 tables, available from JMC as RDB5679)

R-32/125/134a (30/10/60) and (23/25/52) [R-407C] with a polyolester (POE) lubricant (Mobil EAL Arctic® 32) compared to R-22 with an alkylbenzene (AB) lubricant (Shrieve Zerol® 150) in a 17.6 kW (5 ton) split-system heat pump (Carrier 58YKB060) using a hermetic scroll compressor in both the cooling and heating modes

H. W. Sibley (Carrier Corporation), **Drop-In Tests of Refrigerant Blend R-32/125/134a (23/25/52),** Alternative Refrigerants Evaluation Program (AREP) report 180, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1994 (10 pages with 2 figures and 4 tables, available from JMC as RDB5680)

R-407C with a polyolester (POE) lubricant (Mobil EAL Arctic® 32) compared to R-22 with an alkylbenzene (AB) lubricant (Shrieve Zerol® 150) in a 17.6 kW (5 ton) split-system heat pump (Carrier 58YKB060) using a hermetic scroll compressor in the cooling mode with nominal and 30% higher charge of lubricant

W. K. Snelson, J. W. Linton, A. R. Triebe, and P. F. Hearty (National Research Council, Canada, NRCC), **System Drop-In Tests of Refrigerant Blend R-125/R-143a/R-134a (44%/52%/4%) Compared to R-502**, paper 3834, *Transactions* (Winter Meeting, Chicago, IL, 28 January - 1 February 1995), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(1):17-24, 1995 (8 pages with 12 figures, RDB5230)

R-404A [R-125/143a/134a (44/52/4)] and R-502

K. E. Starner (York International Corporation), **Drop-In Test of Refrigerant R-134a**, Alternative Refrigerants Evaluation Program (AREP) report 88, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1993 (6 pages with 2 tables, available from JMC as RDB3C88)

This report summarizes "drop-in" performance tests of R-134a in two water-cooled chillers with nominal capacities of 1.4 and 2.3 MW (390 and 650 tons) for R-22. Both employed open-drive, screw compressors (Frick). Approximately 39% of the evaporator and condenser tubes were plugged in the larger chiller for R-134a tests, to simulate down-sized heat exchangers. The report describes the test equipment and conditions and provides tabular results and comparative R-22 measurements. The entering and leaving water temperatures, flow rates, refrigerant pressures, and subcooled-refrigerant temperature are provided. A second table gives the capacity, input power, specific power (reciprocal of efficiency), and compressor isentropic and volumetric efficiencies for R-134a normalized to those for R-22. The report concludes that the chiller capacities were 33% lower, isentropic compressor efficiencies 2% lower, volumetric efficiencies 2% higher, and overall efficiency within approximately 2% for R-134a compared to R-22. Even with the reduced heat transfer surface area, the large chiller efficiency fell only slightly, approximately 2%. The R-134a tests were performed with a polyolester lubricant (CPI® Solest®).

Y. Sumida (Mitsubishi Electric Corporation, Japan), **Drop-In Test of Refrigerant Blend R-125/143a/-134a (44/52/4),** Alternative Refrigerants Evaluation Program (AREP) report 49, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, April 1993 (20 pages with 11 figures and 7 tables, available from JMC as RDB3849)

R-404A

Y. Tanimura (Mitsubishi Electric Corporation, Japan), **Drop-In Test of Refrigerant Blend R-32/125/134a (23/25/52),** Alternative Refrigerants Evaluation Program (AREP) report 137, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, December 1993 (8 pages with 5 figures and 2 tables, available from JMC as RDB4737)

This report summarizes performance measurements of R-407C [R-32/125/134a (23/25/52)] and R-32/125/134a (30/10/60) with an unidentified ester lubricant. They were tested in a 2.6 kW (8900 Btu/hr) split-system room air conditioner (RAC) / heat pump with a rotary, rolling-piston compressor. The results are compared to corresponding data for R-22 with an unidentified mineral oil. Schematics illustrate the refrigerant circuits in both the heating and cooling modes. The data for the two modes are tabulated. The charge and lubricant quantities as well as the test conditions are indicated. Operating temperatures and pressures are given for the inlets and outlets of the compressor, condenser, expansion device, and evaporator. The results for both refrigerants show capacity changes of less than 1% in either the cooling and heating modes. The coefficients of performance (COPs) dropped by 3% and less than 1% in the cooling mode, with R-407C and R-32/125/134a (30/10/60). The heating COPs decreased by 7 and 4%, respectively. The report notes that the compressor discharge pressures is higher in both modes with both blends, but the discharge temperatures are lower.

C-S. Wei, S-P. Lin, and C-C. Wang (Industrial Technology Research Institute, ITRI, Taiwan), **System**

Performance of a Split-Type Unit Having R-22 and R-407C as Working Fluids, paper PH-97-10-1, *Transactions* (Winter Meeting, Philadelphia, PA, 26-29 January 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 103(1):797-802, 1997 (6 pages with 6 figures and 2 tables, RDB7C19)

P. Weiss, M. Barreau, and S. Macaudiere (Elf Atochem S.A., France), **Field Tests Using HCFC-22 Replacements,** *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:606-613, 1995 (8 pages with 6 figures and 1 table, rdb5A07)

This paper summarizes a laboratory comparison of the performance of four potential R-22 replacements in a water-to-water heat pump, for both the heating and cooling modes. R-22 was tested with an alkylbenzene lubricant as a reference. R-134a, R-404A, R-407C, and R-23/32/-134a (4.5/21.5/72) [FX220, believed to be (4.5/-21.5/74)] were tested with an unidentified polyolester lubricant. The paper shows a schematic of the test system and describes the test conditions and measured data points. The evaporator inlet and outlet temperatures, suction and discharge temperatures and pressures, and flow rates are tabulated for all five refrigerants for condenser water temperatures of 30 and 50 °C (86 and 122 °F). Plots compare the capacities and efficiencies of the five refrigerants in both the heating and cooling modes. A final plot shows the discharge pressures for a range of condenser water temperatures. The paper concludes that R-407C or the R-23/32/134a blend offer the best match for R-22 for air-cooled systems. It notes that R-134a is an attractive candidate for large chillers, but that R-404A is the optimum choice for smaller chillers when a high cooling capacity is one of the key criteria. The tests were performed at the TNO Institute of Environmental and Energy Technology in the Netherlands.

R. Yajima and O. Kataoka (Daikin Industries, Limited, Japan), **Drop-In Test of Refrigerant Blends R-32/134a (30/70) and R-32/125/134a (23/25/52),** Alternative Refrigerants Evaluation Program (AREP) report 152, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1994 (10 pages with 1 figure and 2 tables, available from JMC as RDB4752)

This report summarizes performance tests of R-32/134a (30/70) and R-407C with an unidentified ester lubricant. They were tested in an unmodified 7.6 kW (2 ton) split-system, unitary heat pump with a 2.2 kW (3 hp) scroll compressor. The equipment is shown schematically. The results are tabulated with corresponding data for R-22 with an unidentified mineral oil. The charge and lubricant quantities and the test conditions are indicated. Operating temperatures and pressures are given for the inlets and outlets of the compressor and evaporator as well as the outlets from the condenser and expansion device. The results show capacity and efficiency losses of 1.4 and 5.8%, respectively in the cooling mode, and a capacity increase of 4% and efficiency decrease of 3.5% in the heating mode, for R-32/134a (30/70). They also show a capacity increase of 1.2% and efficiency decrease of 1% in the cooling mode, and capacity and efficiency increases of less than 1% in the heating mode, for R-407C.

Optimized Compressor Tests

R. Aarlien and P. E. Frivik (SINTEF Energy Research AS, Norway), **Comparison of Practical Performance Between CO_2 and R-22 Reversible Heat Pumps for Residential Use,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 388-398, 1998 (11 pages with 11 figures and 3 tables, RDB9242)

summarizes laboratory comparisons of transcritical R-744 (carbon dioxide) and conventional R-22 air-to-air, split-system heat pumps for residential use; concludes that the overall coefficient of performance (COP) of the R-744 system is competitive, though the measured heating and cooling COPs were 3-14% higher and 0.5-14% lower, respectively; notes that the heat exchanger design of the prototype R-744 system is not optimal and that water retention caused fluctuating system pressures; also, the R-744 compressor experience bearing wear and refrigerant leakage; identifies areas for improvement; includes discussion by V. W. Goldschmidt (Purdue University, USA), S. H. Jørgensen (Danfoss A/S, Denmark), and D. P. Davidson (Driver Technology Limited, UK)

T. Boyman, P. Lochmann, and A. Steiner (T. Boyman ZTL), **Experiments and Experiences with Small Vapor Compression Refrigeration Plants with Ammonia and Miscible Oil,** *Heat Transfer Issues in Natural Refrigerants* (proceedings of the IIR Conference - meeting of Commissions B1, E1, and E2, University of Maryland, College Park, MD, 6-7 November 1997), publication 1997/5, International Institute of Refrigeration (IIR), Paris, France, 203-220, 1997 (18 pages with 20 figures, RDB9820)

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laboratory and field tests of 15 kW (4.3 ton) refrigeration systems using R-717 (ammonia) and a miscible polyglycol lubricant for evaporation temperatures of -15 to 0 °C (5 to 32 °F): detailed description and performance analysis; includes an evaporator simulation; notes that the R-717 flow rate is very low requiring an effective distribution system for parallel coils

K. Furuhama (Toshiba Corporation, Japan), **Soft-Optimized Compressor Test of Refrigerant Blend R-32/125 (50/50)**, Alternative Refrigerants Evaluation Program (AREP) report 163, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1994 (18 pages with 7 figures and 6 tables, available from JMC as RDB5663)

R-410A compared to R-22 in a rotary, rolling-piston compressor with an unidentified polyolester lubricant

N. Kanzaki (Kobe Steel, Limited, Japan), **Soft-Optimized Compressor Test of Refrigerant R-134a**, Alternative Refrigerants Evaluation Program (AREP) report 85, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1993 (12 pages with 8 tables, available from JMC as RDB3C85)

Y. Morikawa (Matsushita Electric Industrial Company Limited, Japan), **Procedure and Report Format for Soft-Optimized Compressor Tests Performed by JRAIA Member Companies**, Alternative Refrigerants Evaluation Program (AREP) report 81 Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1993 (8 pages with 2 tables, available from JMC as RDB3C81)

Optimized System Tests

R. S. Agarwal, M. Ramaswarmy, A. Kant, V. Agarwal, and V. K. Srivastava (Indian Institute of Technology, India), **Evaluation of Hydrocarbon Refrigerants in Single Evaporator Domestic Refrigerator-Freezers**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 248-257, October 1995 (10 pages with 10 figures and 4 tables, available from JMC as RDB5A66)

R-12, R-134a, R-600a, R-290/600a (50/50), capacity, efficiency, run time, pull down, ice making

G. Ahnefeld and E. Wobst (Institut für Luft- und Kältetechnik Dresden, ILK, Germany), **Performance Comparison of a Zeotropic Refrigerant Blend with HCFC-22**, *Ki Luft- und Kältetechnik*, 31(3):134-138, March 1995 (5 pages in German, rdb8C10)

comparisons of R-404A, R-407A, R-407B, R-407C, R-410A, and R-507A to R-22 with constant refrigerating capacity and evaporating and condensing temperatures, but different compressor speeds

J. Berge, S. L. Kwon, and L. Naley (Thermo King Corporation), **Soft-Optimized System Test of Refrigerant Blend R-125/143a/134a (44/52/4),** Alternative Refrigerants Evaluation Program (AREP) report 176, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1994 (20 pages with 4 figures and 5 tables, available from JMC as RDB5676)

R-404A with an unidentified polyolester (POE) lubricant compared to R-502 with an alkylbenzene (AB) lubricant in a 14 kW (4 ton) transport refrigeration unit using an engine-driven, reciprocating piston compressor

A. Földi, **Untersuchung von CO_2- und R-134a-Fahrzeugkälteanlagen mit geregeltem Hubkolbenverdichter unter fahrzeug- und fahrgerechten Betriebsbedingungen** [Investigation of CO_2 and R-134a Vehicle Air-Conditioning Systems with Standard Reciprocating-Piston Compressors under Vehicle and Standardized Test Conditions], PhD thesis, Technische Universität München (TUM), Germany, circa 1998 (RDB9228)

summarizes vehicle and laboratory bench tests mobile air conditioning systems (MACS) using of R-134a and R-744 (carbon dioxide): concludes that R-744 systems offer sufficient cooling capacity for comfort in all ambient conditions and have comparable fuel consumption to R-134a systems at steady-state operating conditions; also concludes that the R-744 system offers a lower total equivalent warming impact (TEWI) and that the estimated weight increase for it would have "no remarkable influence" on fuel consumption - as reported in RDB9226

A. Fujitaka, N. Yamaguchi, and Y. Watanabe (Matsushita Electric Industrial Company Limited, Japan), **Experimental Evaluation of Room Air Conditioner Using R-32/125/134a Blend**, paper 2.1, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 17-22, December 1994 (6 pages with 20 figures and 4 tables; in Japanese with abstract, figures, and tables in English; RDB5404)

R-22, R-407C

K. Furuhama and M. Komazaki (Toshiba Corporation, Japan), **Performance Evaluation of Resi-**

dential Air Conditioner with HFC32/125 Mixture, paper 2.2, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 -Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 23-26, December 1994 (4 pages with 5 figures and 2 tables; in Japanese with abstract, figures, and tables in English; RDB5405)

R-22; R-32; R-125; R-32/125 (40/60), (50/50), (60/40), and (80/20); zeotrope, blend composition, efficiency, COP

P. R. Glamm, E. F. Keuper, and F. B. Hamm (The Trane Company), **Evaluation of HFC-245ca for Commercial Use in Low Pressure Chillers**, report DOE/CE/23810-67 volume 1, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, March 1996 (96 pages with 46 figures and 16 tables, available from JMC as RDB6501)

This report summarizes theoretical and experimental performance comparisons of R-245ca with both R-11 and R-123, for which it is a potential replacement, in a multistage, centrifugal chiller. It also addresses environmental advantages and safety concerns, notably including the marginal flammability of R-245ca. The report outlines the theoretical approach used and comments on the lubricant impacts, operating range, impeller selection, compressor performance, and heat exchanger differences for R-245ca substitution. It also discusses attempts to use a blend of R-245ca and a mix of perfluorohexane isomers, proposed to suppress flammability. This blend was found to be unsatisfactory due to reduced surface tension and resultant liquid carryover. The study concludes with an assessment of commercial viability for both retrofit and new applications. The report provides detailed plots and tabular data for component operating characteristics and performance. An appendix addresses surge limits for the three refrigerants. A second appendix provides detailed records of operating parameters, in both inch-pound (IP) and metric (SI) units of measure, for three selections of impellers, sized for each of the refrigerants. The report concludes that R-245ca will not perform satisfactorily in retrofits of equipment designed for R-11 and R-123, due to surge concerns, without a compressor replacement and, in most cases, a larger motor and drive system. The expense would be prohibitive except in special cases. R-245ca can match the performance of R-123 in new equipment with a small increase in heat transfer surface, but this change is not currently viable since R-245ca is not commercially produced. Moreover, concerns with flammability would result in market resistance. Blending R-245ca with flammability-suppressants would degrade performance and complicate heat exchanger design. The report recommends that industry continue to investigate cost-effective means to use marginally flammable refrigerants that offer high performance.

P. R. Glamm, E. F. Keuper, and F. B. Hamm (The Trane Company), **Evaluation of HFC-245ca for Commercial Use in Low Pressure Chillers: Chiller Test Data**, report DOE/CE/23810-67 volume II, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, March 1996 (414 pages all tables, available from JMC as RDB6502)

This report provides detailed chiller test data for R-11 with a mineral oil and a polyolester (POE) lubricant (CPI Solest 68) and for R-123 and R-245ca with the same POE in a three-stage, centrifugal chiller (Trane CenTraVac CVHE). R-11 and R-245ca were run with two sets of impeller selections, and R-123 with three; these selections include optimized choices for each of the three refrigerants. The test data cover multiple runs to optimize the charge size and test different operating and load conditions. Curve fits are provided for motor efficiency and speed. These detailed measurements substantiate the data plots and comparisons provided in volume 1 of this report.

P. R. Glamm (The Trane Company), **Water-Source Heat Pumps with HFC Refrigerants**, *IEA Heat Pump Center Newsletter - CFC and HFC Replacement*, International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, 13(1):25-28, March 1995 (4 pages with 3 figures and 5 tables, RDB5688)

R-407C and R-410A performance in a 10.6 kW (3 ton) water-source heat pump compared to R-22

D. S. Godwin (Air-Conditioning and Refrigeration Institute, ARI), **Results of Soft-Optimized System Tests in ARI's R-22 Alternative Refrigerants Evaluation Program**, *Proceedings of the 1994 International Refrigeration Conference at Purdue,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 7-12, July 1994 (6 pages with 4 figures; 8 page reprint available from JMC as RDB4802)

AREP

J. Hellmann (Solvay Fluor und Derivate GmbH, Germany) and R. Döring (Fachhochschule Münster, Germany), **Vergleich der Kältemittel R22, R410A, und R-407C in einer Kälteanlage** [Comparison of the Refrigerants R-22, R-410A, and R407C in a Refrigeration System], *Ki Luft- und Kälte-*

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technik, 33(4):159-166, April 1997 (8 pages in German, rdb8C11)

theoretical and experimental performance comparison of R-407C and R-410A to R-22 for commercial refrigeration conditions

H. M. Hughes and S. J. Feldman (AlliedSignal Incorporated), **Performance of HCFC-22 Alternative Refrigerants in a Residential Split-System Air Conditioner,** *Proceedings of the AIRAH Conference* (Melbourne, Australia, 1-3 May 1995, Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH), Parkville, Victoria, Australia, 1995 (rdb9847)

Y. H. Hwang and R. K. Radermacher (University of Maryland), **Experimental Evaluation of CO_2 Water Heater,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 368-375, 1998 (8 pages with 7 figures and 1 table, RDB9236)

presents laboratory test results for a prototype heat pump water heater (HPWH) using R-744 (carbon dioxide) in a transcritical cycle; indicates a 10% performance advantage over R-22; includes discussion by D. C. Zeitlow (Visteon, USA) and M. S. Kim (Seoul National University, Korea)

Y. H. Hwang, J. F. Judge, and R. K. Radermacher (University of Maryland), **Experience with Refrigerant Mixtures,** paper PH-97-9-3, *Transactions* (Winter Meeting, Philadelphia, PA; 26-29 January 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 103(1):765-776, 1997 (12 pages with 20 figures and 4 tables, RDB7C16)

summarizes laboratory tests of blends in air-to-air heat pumps and the time-dependent operating compositions: presents a transient simulation program and validation studies to estimate the behavior of blends in different types of heat exchangers and the performance of heat pumps using them; the blends addressed in the paper include R-407C, R-32/123 (80/20), and R-32/-134a (30/70); concludes that heat exchanger and system optimization are important to maximize performance with zeotropes, a near-counterflow heat exchanger can improve performance by 10%, and there are internal composition shifts with predictable effects; paper includes discussion by J. Lebrun (Université de Liege, Belgium) and the authors' response lubricant and refrigerant-lubricant miscibility effects

Y. H. Hwang, J. F. Judge, and R. K. Radermacher (University of Maryland), **An Experimental Evaluation of Medium and High Pressure HFC Replacements for R-22,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 41-48, October 1995 (8 pages with 7 figures and 9 tables, available from JMC as RDB5A44)

performance of R-407C, R-410A, and R-410B in a laboratory test facility

S. Ishigaki (Sanyo Electric Company, Limited, Japan), **Performance Improvement of 1 HP RAC with Refrigerant Mixture R-32/125/134a,** paper 2.5, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 38-41, December 1994 (4 pages with 6 figures and 3 tables; in Japanese with abstract, figures, and tables in English; RDB5408)

R-32/125/134a (23/25/52) [R-407C]

M. Katayama (Fujitsu General Limited, Japan), **Soft-Optimized System Test of Refrigerant Blend R-32/125/134a (23/25/52),** Alternative Refrigerants Evaluation Program (AREP) report 167, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, May 1994 (16 pages with 10 figures and 2 tables, available from JMC as RDB5667)

R-407C with an polyolester lubricant (JS4156A1) compared to R-22 with mineral oil (Witco Suniso® 4GSD) in a room heat pump, with and adjustable-speed rotary, rolling-piston compressor, in both the cooling and heating modes

S. L. Kwon (Thermo King Corporation), **Implementation of Ozone Safe Alternative Refrigerant Mixtures in Transport Refrigeration Systems: Challenges and Opportunities,** *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 134-142, November 1997 (9 pages with 10 figures and 3 tables, RDB8338)

rationale for selection of R-404A as a replacement for R-502 in transport refrigeration systems: development and modification of system components; evaluation of composition shifts; test facility, procedures, and results; concludes that equipment designed for R-502 achieves essentially the same performance with R-502 with little or no modification and improved efficiency with optimization

M. Kurachi (Matsushita Refrigeration Company, Japan), **Soft-Optimized System Test of Refrigerant Blend R-32/125/134a (23/25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 166, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, February 1994 (10 pages with 1 figure and 4 tables, available from JMC as RDB5666)

R-407C with an unidentified polyolester lubricant compared to R-22 with mineral oil in a room heat pump, with and adjustable-speed scroll compressor, in both the cooling and heating modes

A. T. Lim (Inter-City Products Corporation), **Soft Optimized System Test of Refrigerant Blend R-32/125/134a (23/25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 162, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, May 1994 (4 pages with 1 table, available from JMC as RDB5662)

This report consists of a single table that compares the measured performance and operating parameters of R-407C and R-22 in a packaged-terminal air conditioner. The zeotropic blend was tested in drop-in and three soft-optimized modes. They included matching of the superheat and subcooling, coil modification for recircuiting, and coil modification for counterflow circuiting. An unidentified polyolester (POE) lubricant was used with both refrigerants. The blend results show steady state losses of 7.3-10.8% in efficiency and 2.5-6.0% in capacity. The report gives the measured temperatures and pressures for key locations, power draw, sensible and latent cooling capacities, and counts of expansion valve openings.

J. W. Linton, W. K. Snelson, A. R. Triebe, and P. F. Hearty (National Research Council, Canada, NRCC), **System Performance Comparison of R-507 with R-502**, paper 3925, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):502-510, 1995 (9 pages with 13 figures, RDB6363)

laboratory performance tests compared R-507A to R-502 at evaporating temperatures of -30 to -15 °C (-22 to 5 °F) and 43.3 and 54.4 °C (110 and 130 °F) condensing: the evaporator capacity with R-507A was found to be 95-105% of that for R-502, depending on the operating conditions and the amount of liquid subcooling present; R-507A was less energy efficient for all conditions tested with a 3-13% lower coefficient of performance (COP)

J. W. Linton, W. K. Snelson, A. R. Triebe, and P. F. Hearty (National Research Council, Canada, NRCC), **Soft-Optimization Test Results of R-32/-R-125/R-134a (10%/70%/20%) Compared to R-502**, paper OR-94-1-4, *Transactions* (Annual Meeting, Orlando, FL, 25-29 June 1994), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 100(2):558-565, 1994 (8 pages with 13 figures, RDB4704)

soft optimization, laboratory tests to compare the system performance of R-407B [R-32/125/134a (10/70/20)] with that of R-502: tests were conducted using an open-drive, reciprocating-piston compressor and counterflow, tube-in-tube heat exchangers; paper presents compressor performance characteristics including shaft power, pressure ratio, and compressor discharge temperature along with the evaporator capacity, refrigerant mass flow, and cooling coefficient of performance (COP); effects of additional liquid subcooling on the evaporator capacity and COP are discussed

K. Matsuo (Hitachi, Limited, Japan), **Practical Experiences with Refrigerant Blend R-407C,** Alternative Refrigerants Evaluation Program (AREP) report 187, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1995 (12 pages with 7 figures 1 table, available from JMC as RDB7651)

laboratory tests of the performance of R-407C with an ester lubricant in a split-system, air-to-air heat pump using a scroll compressor and composition maintenance; deviation in the composition is minimized by storing liquid refrigerant in a receiver on the high-pressure side of the circuit rather than in an accumulator on the low-side; method improves the heating and cooling mode coefficients of performance (COPs) by 6% and 10% respectively

M. Mårtensson and E. Skoglund, **Cycle Performance Test of R404A and R407A Using a Scroll Compressor**, MS thesis, Kungliga Tekniska Högskolan (KTH), Stockholm, Sweden, 1996 (rdb6760)

R-404A, R-407A

Y. Morikawa (Matsushita Electric Industrial Company Limited, Japan), **Procedure and Report Format for Soft-Optimized System Tests Performed by JRAIA Member Companies,** Alternative Refrigerants Evaluation Program (AREP) report 80, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1993 (10 pages with 4 tables, available from JMC as RDB3C80)

AREP

F. T. Murphy, R. E. Low, B. E. Gilbert (ICI Klea), J. W. Linton, W. K. Snelson, and P. T. Hearty (National Research Council, Canada, NRCC), **Comparison of R-407C and R-410A with R-22 in a 10.5 kW (3.0 TR) Residential Central Air-Conditioner**, *Stratospheric Ozone Protection for the 90's* (pro-

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ceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 31-40, October 1995 (10 pages with 5 figures and 3 tables, available from JMC as RDB5A43)

R-22, R-407C, R-410A, polyolester lubricant, laboratory performance test

M. Ozu (Toshiba Corporation, Japan), **Soft-Optimized System Test of Refrigerant Blend R-32/-125/134a (23/25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 149, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1994 (10 pages with 3 figures and 3 tables, available from JMC as RDB4749)

This report summarizes a performance test of R-407C with an unidentified ester lubricant in a 2.3 kW (8000 Btu/hr) room air conditioner (RAC) / heat pump. The results are tabulated with corresponding data for R-22 with an unidentified mineral oil.

M. Pande, Y. H. Hwang, J. F. Judge, and R. K. Radermacher (University of Maryland), **An Experimental Evaluation of Flammable and Nonflammable High Pressure HFC Replacements for R-22**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 21-26, July 1996 (6 pages with 4 figures and 7 tables, RDB6752)

performance comparison of R-32, R-410A, and R-410B with R-32 in a residential, air-to-air heat pump; indicates 5.1% and 2.5-4% improvement in cooling and heating seasonal performance, respectively, for R-32, but notes that it is flammable; indicates a 2-3% improvement for R-410A and R-410B for cooling and similar performance for heating; summarizes tests at standard rating conditions and provides plots of efficiency and capacity relative to charge amount; tabulates seasonal performance for heating (for the six standard rating regions for the United States) and cooling for the cited refrigerants

K. Sakuma (Mitsubishi Electric Corporation, Japan), **Soft-Optimized System Test of Refrigerant R-134a**, Alternative Refrigerants Evaluation Program (AREP) report 84, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1993 (8 pages with 4 figures and 2 tables, available from JMC as RDB3C84)

N. Sawada (Sanyo Electric Company, Limited, Japan), **Soft-Optimized System Test of Refrigerant Blend R-32/125/134a (23/25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 150, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, December 1993 (10 pages with 3 figures and 5 tables, available from JMC as RDB-4750)

This report summarizes a performance test of R-407C with an unidentified polyester lubricant in a 2.6 kW (9400 Btu/hr) room air conditioner (RAC) / heat pump. The results are tabulated with corresponding data for R-22 with a mineral oil (Witco Suniso® 4GSD-T).

H. W. Sibley (Carrier Corporation), **Soft-Optimized System Test of Refrigerant Blends R-32/125 (60/40) and R-32/125 (50/50)**, Alternative Refrigerants Evaluation Program (AREP) report 95, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, October 1993 (6 pages with 2 tables, available from JMC as RDB3C95)

R-32/125 (50/50) [R-410A] and R-32/125 (60/40)

H. W. Sibley (Carrier Corporation), **Soft-Optimized System Test of Refrigerant Blends R-32/125/134a (30/10/60), R-32/125/134a (25/20/55), and R-32/125/134a (23/25/52)**, Alternative Refrigerants Evaluation Program (AREP) report 96, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, October 1993 (8 pages with 3 tables, available from JMC as RDB3C96)

R-32/125/134a (30/10/60), R-32/125/134a (25/20/55), and R-32/125/134a (23/25/52) [R-407C]

W. K. Snelson, J. W. Linton, P. F. Hearty and A. R. Triebe (National Research Council, Canada, NRCC), **Soft-Optimized Test Results of R-32/125/134a (20/40/40)**, Alternative Refrigerants Evaluation Program (AREP) report 155, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, January 1994 (18 pages with 5 figures and 4 tables, available from JMC as RDB4755)

R-407A with unidentified ester lubricant compared to R-502 with unidentified alkylbenzene in a test loop with a reciprocating-piston compressor

W. K. Snelson, J. W. Linton, P. F. Hearty and A. R. Triebe (National Research Council, Canada, NRCC), **Soft-Optimized Test Results of R-125/143a (50/50)**, Alternative Refrigerants Evaluation Program (AREP) report 130, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, December 1993 (16 pages with 5 figures and 4 tables, available from JMC as RDB3D30)

R-507A with unidentified ester lubricant compared to R-502 with unidentified alkylbenzene in a test loop with a reciprocating-piston compressor

W. K. Snelson, J. W. Linton, P. F. Hearty, and A. R. Triebe (National Research Council, Canada, NRCC), **Soft-Optimized System Test of Refrigerant Blend R-32/125/134a (10/70/20)**, Alternative Refrigerants Evaluation Program (AREP) report 94, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, October 1993 (44 pages with 4 figures and 16 tables, available from JMC as RDB3C94)

R-407B

W. K. Snelson, J. W. Linton, P. F. Hearty, and A. R. Triebe (National Research Council, Canada, NRCC), **Soft-Optimized System Test of Refrigerant Blend R-125/143a/134a (44/52/4)**, Alternative Refrigerants Evaluation Program (AREP) report 92, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1993 (16 pages with 5 figures and 4 tables, available from JMC as RDB3C92)

R-404A and R-502

M. Sonnekalb and J. Köhler (Konvecta / IPEK, Germany), **Transport Refrigeration with a Transcritical Cycle Using Carbon Dioxide as Refrigerant**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 124-133, November 1997 (10 pages with 5 figures and 2 tables, RDB8335)

laboratory performance tests of optimized transport refrigeration systems using R-502, R-507A, and R-744 (carbon dioxide): tests were conducted on 4 kW (13,600 Btuh) systems employing open reciprocating-piston compressors (Bock FKX 3) modified for each refrigerant; the heat exchangers were made with steel instead of copper tubes for R-744 to withstand the higher pressures; the measured coefficient of performance (COP) with R-744 in a transcritical cycle was 15% lower than R-502 in a conventional vapor-compression cycle, but 18% higher than for R-507A; authors conclude that R-744 should be used instead of the fluorochemical alternatives in light on the leakage rates of refrigerants from transport refrigeration units and the high global warming potentials (GWP) or hydrofluorocarbon (HFC) refrigerants

M. W. Spatz, H. M. Hughes, and J. Zheng (AlliedSignal Incorporated), **Experimental Evaluation of R-22 Alternative Refrigerants in Typical Split-System Heat Pump**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:-1244-1253, 1995 (10 pages with 4 tables, rdb8310)

performance tests of R-22, R-407C (R-32/125/-134a (23/25/52)], and R-410A, R-134a, R-410A [R-32/125 (50/50), identified in the paper by AlliedSignal's trade name AZ-20] in an air-to-air, split-system, unitary heat pump: the results show R-407C to yield 4-9% lower and R-410A to offer 3-5% higher efficiency than R-22

K. E. Starner (York International Corporation), **Practical Experiences with Refrigerant Blend R-404A**, Alternative Refrigerants Evaluation Program (AREP) report 186, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, June 1995 (8 pages with 2 tables, available from JMC as RDB7648)

presentation charts on laboratory tests to compare R-22 and R-404A performance in a 950 kW (270 ton), water-cooled chiller, employing a twin-screw compressor, in a test loop; the lubricant used with R-22 is not indicated, but is likely to have been a mineral oil; the lubricant used with R-404A was a polyolester (CPI® Solest® 68); comparative operating conditions are tabulated; overall, capacity and efficiency were 1% higher and 13% lower, respectively, with R-404A; the condensing temperature increased and evaporator temperature decreased with R-404A; the lower evaporating temperature was confirmed in independent pool-boiling tests

Y. Sumida (Mitsubishi Electric Corporation, Japan), **Soft-Optimized System Test of Refrigerant Blend R-125/143a/134a (44/52/4),** Alternative Refrigerants Evaluation Program (AREP) report 101, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, October 1993 (12 pages with 8 figures and 4 tables, available from JMC as RDB3D01)

R-404A

L. J. Swatkowski, Jr. (Appliance Industry-Government CFC Replacement Consortium), **Energy Efficiency of HFC-134a versus HFC-152a**, *Proceedings of the 44th Annual International Appliance Technical Conference* (University of Ohio, Columbus, OH, 11 May 1993), IATC, Batavia, IL, May 1993; reprint published by the Association of Home Appliance Manufacturers (AHAM), Chicago, IL, May 1993 (9 pages, available from JMC as RDB3722)

This paper summarizes a project to evaluate the relative efficiencies of R-134a and R-152a in household refrigerators and freezers typical of those used in the United States. The project was conducted by the Appliance Industry-Government CFC Replacement Consortium, also known as the *Appliance Research Consortium* (ARC). The paper reviews the organization and membership of ARC and mentions that 21 projects have been initiated and three of them completed since 1989. It reviews the history of the present project, noting a 1991 comparison showing higher efficiency for R-152a in unoptimized, *drop-in* comparisons. Those findings

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were challenged by another study (see RDB-2728). The paper outlines testing by the Environmental Protection Agency (EPA) and six equipment manufacturers, using refrigerator-freezers incorporating compressors optimized for each refrigerant. The paper reviews test unit criteria, test methods, refrigerant supply, and lubricant and desiccant selection. It presents arguments for and against adjusting the measured data, and notes a conclusion by the program participants not to do so. The paper gives the study's conclusion, that no statistically Significant difference in efficiency was found between R-134a and R-152a.

K. Takaichi, O. Asakawa, Y. Masatoki, R. Fujimoto (Matsushita Refrigeration Company, Japan), Y. Yoshida (Matsushita Electric Industrial Company, Limited, Japan), **New Application of R502 Substitute Refrigerant into Freezer-Refrigerator**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 389-394, July 1994 (6 pages with 3 figures and 3 tables, RDB4851)

R-502/13 (87/13), R-22/115/12 (42.5/44.5/13), R-125/143a/134a (40/50/10), R-404A [R-125/-143a/134a (44/52/4)], R-507A [R-125/143a (50/50)], R-32/125/134a (20/40/40) and (30/-10/60)], R-32/125/134 (20/50/30), R-134a

A. R. Triebe, W. K. Snelson, P. F. Hearty, J. W. Linton (National Research Council, Canada, NRCC), F. T. Murphy, and S. Corr (ICI Klea, UK), **System Performance Comparison of R-407A and R-502 in Parallel and Counter-flow Heat Exchangers**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 45-50, July 1996 (6 pages with 6 figures, RDB6756)

performance comparison of R-407A and R-502 based on measurements in a test loop; performance with R-407A was found to be 96-105% and 96-99% that of R-502 by switching from a parallel to counter-flow heat exchanger at -15 °C (5 °F) and -25 °C (-13 °F) evaporating temperature, respectively; the maximum performance increase with a counter-flow condenser was found to be 3%

E. A. Vineyard (Oak Ridge National Laboratory, ORNL) and L. J. Swatkowski, Jr. (Appliance Industry-Government CFC Replacement Consortium), **Energy Efficiency of HFC-134a versus HFC-152a**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC), Alliance for Responsible CFC Policy, Arlington, VA, 86-91, October 1993 (6 pages with 1 figure and 1 table, RDB3A30)

R-134a, R-152a, performance

Q. Wang and J. L. Cox (Rheem Manufacturing Company), **Soft-Optimized System Test of Refrigerant Blends R-32/125 (50/50) and R-32/-125/134a (23/25/53)** (sic), Alternative Refrigerants Evaluation Program (AREP) report 131, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, December 1993 (16 pages with 7 tables, available from JMC as RDB3D31)

R-407C [R-32/125/134a (23/25/52)] and R-410A

E. Wobst and G. Ahnefeld (Institut für Luft- und Kältetechnik Dresden, ILK, Germany), **Anlagenleistungsmessungen mit R410A** [Equipment Capacity Measurements with R-410A], Solvay Fluor und Derivate GmbH, Hannover, Germany, 1997 (in German, RDB9846)

compressor tests with R-22, R-134a, R-290 (propane), R-407C, and R-410A

R. Yajima, S. Taira, and I. Tarutani (Daikin Industries Limited, Japan), **The Performance Evaluation of Various HFC Refrigerant Mixtures,** paper 2.3, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan 27-32 December 1994 (6 pages with 9 figures and 3 tables; in Japanese with abstract, figures, and tables in English; RDB5406)

R-22; R-32; R-125; R-134a; R-32/134a (30/70); R-32/125 (60/40); R-125/134a (40/60); R-32/125/134a (30/10/60), (23/25/52) [R-407C], and (18/40/42)

M. G. Yarrall, S. D. White, D. J. Cleland (Massey University, New Zealand), R. D. S. Kallu (Energy Services Group, ECNZ, New Zealand), and R. A. Hedley (Flotech Limited, New Zealand), **Performance of a Transcritical CO_2 Heat Pump for the Food Processing Industries**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 203-211, 1998 (9 pages with 5 figures and 1 table, RDB9214)

summarizes performances tests of a prototype heat pump using R-744 (carbon dioxide) in a transcritical cycle for simultaneous refrigeration at less than 0 °C (32 °F) and water heating at 90 °C (194 °F); system employed an open, oil-free, reciprocating compressor (Knox-Western TP 65) with an adjustable speed drive (ASD); describes the tests and calculations used to determine the cooling and heating coefficients of performance (COPs); concludes that the system achieved a combined cooling and heating COP of approximately 5, which could be improved with an optimized compressor and heat exchangers; includes discussion by A. Adamson (Refrigeration Engineering Pty, Limited, Australia)

Field Tests

R. J. Albrecht (New York State Energy Research and Development Authority, NYSERDA), H. Borhanian (Aspen Systems Incorporated), T. J. Matthews (Hannaford Brothers Company), and L. J. Rafuse (Aspen Systems Incorporated), **Using R-134a and R-22 in Supermarket Refrigeration Applications**, *ASHRAE Journal*, 36(2):30-35, February 1994 (6 pages with 4 figures and 3 tables, RDB4451)

efficiency and materials performance in a field test of R-12 and R-134a in a supermarket; documentation of required modifications for eight systems in the store; no compatibility or operational problems were encountered

T. Andersson, **Field Experience from Refrigeration and Air Conditioning Systems Charged with Hydrocarbons**, *R22 Substitution - Reality or Wishful Thinking* (ASERCOM Symposium, IKK, Essen, 8 October 1997), October 1997 (rdb9309)

M. Barreau, P. Weiss, J. C. Tanguy (Elf Atochem S.A., France), and G. D. Rolotti (Elf Atochem North America), **Field Tests Using R-404A in Large Systems**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 143-152, November 1997 (10 pages with 7 figures and 1 table, RDB8339)

case histories of R-404A use in a frozen food warehouse, an industrial refrigeration process, and a test chamber

M. A. Di Flora (Bristol Compressors, Incorporated), **Practical Experiences with Refrigerant R-134a and Refrigerant Blends R-404A, R-407C, R-410A, and R-507**, Alternative Refrigerants Evaluation Program (AREP) report 184, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, March 1995 (18 pages with 8 tables, available from JMC as RDB7646)

presentation charts on the required changes for application and performance of hydrofluorocarbon (HFC) refrigerants; tabular comparisons of the capacity, efficiency, and operating characteristics of R-404A, R-502, and R-507A in four compressors for low-temperature use, of R-12 and R-134a In a medium temperature compressor, and of R-134a, R-407C, R-410A, and R-410B in air-conditioning and heat pump compressors; list of 23 field tests with R-407C; concludes with a summary of required changes to the lubricant, lubrication system, bearings, housings, and compressor displacement for use of HFC refrigerants

J. Köhler and M. Sonnekalb (Konvecta / IPEK, Germany), **A High-Pressure Transcritical Refrigeration Cycle with Carbon Dioxide for Vehicle Air Conditioning,** *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 375-384, November 1997 (10 pages with 5 figures, RDB8348)

provides field test data from use of R-744 (carbon dioxide) in two buses, along with comparative data for a third bus using R-134a, in Bad Hersfeld, Germany: concludes that performance was comparable; presents findings for laboratory and field tests of an open, two-cylinder, reciprocating-piston compressor (Bock FKX3*CO2), derived from an R-134a design with reinforcement of major parts and reduction of the displacement by 75%; describes both initial and improved versions, the latter using annular valves and a reinforced lubrication system; diagrams compare the ideal and real cycles, showing that the second version of the compressor reduced the pressure drop across the discharge valves, but increased the clearance resulting in an overall volumetric efficiency of 81±7% with a lowered, but still high (9.8-10.5 MPa, 1,400-1,500 psia) compressor discharge pressure

P. G. Lundqvist and L. Herbe (Kungliga Tekniska Högskolan, KTH, Sweden), **Laboratory Evaluation and Field Tests of Replacements for R-22 and R502**, *Proceedings of the 1996 International Refrigeration Conference of Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 57-62, July 1996 (6 page with 2 figures and 1 table, RDB6758)

system performance of R-404A, R-407A, and R-407C; phaseout schedule of common refrigerants in Sweden showing completion by 2000 for chlorofluorocarbon (CFC) refrigerants and curtailment of R-22 use by 2002; presents performance data from a simple field test for R-22 and R-407C in milk coolers; discusses methods and limitations for rigorous field tests with sample data for R-22 and R-407C in a 10 kW (34,000 Btu/hr) water-to-water heat pump; plots perfor-

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mance of R-407C relative to that of R-22 for laboratory drop-in tests and performance data for R-404A and R-407A in a scroll compressor with a liquid injection port, tested in single-stage, with an added suction gas heat exchanger, and with an economizer configurations

E. B. Muir (Copeland Corporation), **Practical Experiences with Refrigerant R-134a and Refrigerant Blends R-404A, R-407A, R-407C, R-410A, and R-507**, Alternative Refrigerants Evaluation Program (AREP) report 185, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, March 1995 (8 pages with 1 table, available from JMC as RDB7647)

presentation charts on field tests of hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) refrigerants and polyolester (POE) lubricants for both retrofits and new applications; the refrigerants addressed were R-134a, R-401A, R-401B, R-402A, R-402B, R-404A, R-407A, R-407C, R-410A, and R-507A; the lubricants were Mobil EAL Arctic® 22CC and ICI Emkarate™ RL 32S; field experience revealed no major system or compressor problems with attention to moisture control and lubrication; describes general results with a question on the quality of thermodynamic property data; outlines lubrication and fractionation issues

L. J. Van Essen (Lennox Industries, Incorporated), **Practical Experiences with Refrigerant Blend R-407C**, Alternative Refrigerants Evaluation Program (AREP) report 183, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, March 1995 (14 pages with 2 figures, available from JMC as RDB-7645)

presentation charts on field tests of R-407C in residential, unitary, split-system, air-to-air, heat pumps at ten sites; shows comparative total acid numbers (TAN) based on oil analyses for eight machines after one winter; concludes that there were no signs of wear or problems related to the refrigerant or lubricant

Pipe Sizing and Flow

D. A. Aaron and P. A. Domanski, **An Experimental Investigation and Modeling of the Flow Rate of Refrigerant 22 through the Short Tube Restrictor**, report NISTIR 89-4120, National Institute of Standards and Technology (NIST), Gaithersburg, MD, July 1989 (106 pages with 32 figures and 3 tables, available from NTIS, RDB4730)

R-22

A. Abdul-Razzak, M. Shoukri, and J. S. Chang (McMaster University), **Characteristics of Refrigerant R-134a Liquid-Vapor Two-Phase Flow in a Horizontal Pipe**, paper CH-95-12-1, *Transactions* (Winter Meeting, Chicago, IL, 28 January - 1 February 1995), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(1):953-964, 1995 (12 pages with 11 figures and 1 table, RDB5233)

T. Atwood (AlliedSignal Incorporated), **Pipe Sizing and Pressure Drop Calculations for HFC-134a,** *ASHRAE Journal,* 32(4):62-66, April 1990 (5 pages, RDB0513)

R-134a

Y. Kim, D. L. O'Neal (Texas A&M University), and X. Yuan (Xi'an Jiatong University, China), **Two-Phase Flow of HFC-134a and CFC-12 through Short-Tube Orifices**, paper OR-94-2-2, *Transactions* (Annual Meeting, Orlando, FL, 25-29 June 1994), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 100(2):582-591, 1994 (10 pages with 7 figures and 4 tables, RDB4707)

S. J. Kuehl (Whirlpool Corporation) and V. W. Goldschmidt (Purdue University), **Flow of R-22 through Short-Tube Restrictors**, paper 3603, *Transactions* (Annual Meeting, Baltimore, MD, 27 June - 1 July 1992), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 98(2):59-64, 1992 (6 pages, rdb3215)

H. Wijaya (AlliedSignal Incorporated), **Adiabatic Capillary Tube Test Data for HFC-134a**, *Proceedings of the 1992 International Refrigeration Conference - Energy Efficiency and New Refrigerants,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 1:63-71, July 1992 (9 pages with 9 figures and 3 tables, RDB2714)

R-134a

Charge Inventory Calculations for Evaporating and Condensing Refrigerants Inside Tubes, proposed research project 758-TRP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, in planning (ASH-0758)

This research project is sponsored by ASHRAE Technical Committee 8.4, *Air-to-Refrigerant Heat Transfer Equipment.* Proposals were due at ASHRAE Headquarters by 12 January 1996. Further information is available from the ASHRAE Manager of Research (+ 1-404/636-8400).

ICI Klea Engineers' Tables: KLEA 407B, Version 1.0 SI Units, bulletin CP/10150/1Ed/23/994, ICI Klea, Runcorn, Cheshire, UK, September 1994 (24 pages with 1 figure and 23 tables, RDB6B39)

This bulletin provides detailed data for systems design using R-407B - a zeotropic blend containing R-32, R-125, and R-134a, specifically R-32/125/134a (10/70/20) - in metric (SI) units of measure. An introductory section explains the use of the data and how they were derived. The first tables give the evaporator pressure from the liquid temperature and mean evaporating temperature, the mean evaporator and dewpoint temperatures from the pressure and liquid temperature, the mean condenser pressure and dew- and bubble-point temperatures from the mean temperature, and the condenser bubble-point, mean, and dew-point temperatures from pressure. They cover evaporating temperatures of -40 to +5 °C (-40 to +41 °F) and condensing temperatures of 10-60 °C (50-140 °F). The next set of tables give the maximum recommended suction line capacities for varying suction gas conditions for 10-105 mm (0.4-4.1 ") type L copper tube and 10-100 (0.4-3.9") schedule 40 steel pipe. Further tables give the discharge and liquid line capacities, and recommended minimum capacities for oil entrainment in suction lines for the same line sizes and types. Two final tables provide correction factors to use the capacity tables at other conditions. A chart correlates refrigerant flow rate and unit capacity for mean evaporating and condensing temperatures of -40 to +5 °C (-40 to 41 °F) and condensing temperatures of 20-50 °C (68-122 °F), respectively. ICI's product name for R-407B is Klea® 407B (formerly Klea® 61).

Performance of a Suction-Line Capillary Tube Heat Exchanger with Alternative Refrigerants, research project 948-RP, American Society of Heating Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, September 1997 - August 1999 (ASH0948)

This project includes theoretical analysis and experimental measurements to develop a method to rate refrigerant mass flow though a suction-line, capillary-tube heat exchanger for single-compound refrigerants and azeotropic blends. Tests with R-12, R-22, R-134a, R-152a, and R-600a are planned. The contractor for the work is the Iowa State University of Science and Technology led by M. B. Pate; it is sponsored by ASHRAE Technical Committee 8.8, *Refrigerant System Controls and Accessories.*

Pressure Drop in Refrigerant Suction Lines at High Refrigerant Flux with Oil in Circulation, proposed research project 731-TRP, American Society of Heating Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, in planning (ASH0731)

This research project is sponsored by ASHRAE Technical Committee 10.3, *Refrigerant Piping*.

Recycling, Reclamation, and Disposal

D. Clodic (École des Mines de Paris, France) and F. Sauer (Dehon Service, France), **The Refrigerant Recovery Book,** publication 90371, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1994 (236 pages with 73 figures and 31 tables, available from ASHRAE for $33 to members and $49 for others; RDB4673)

This book describes methods for efficient and economical recovery of refrigerants from a variety of systems. It begins with a review of ozone depletion and global warming with specific focus on the role of chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC), and hydrofluorocarbon (HFC) refrigerants. It then summarizes the phaseout schedule for ozone-depleting substances under the Montreal Protocol, U.S regulations for phaseout and emission reduction, and corresponding restrictions in the European Community. The book presents recovery devices and methods, including recovery cylinders, equipment for recovery in the vapor and liquid phases, and procedures. It reviews considerations and quality requirements for recycling, reclaim, and disposal with attention to ISO Standard 11650R and ARI Standard 700. It also outlines accepted destruction methods. The book then presents nine case studies covering domestic refrigerators, a small cold room (refrigerated walk-in box), a supermarket, transport refrigeration systems, an industrial plant, R-11 and R-113 centrifugal chillers, railway car air-conditioning units, and automotive air conditioners. It provides a questionnaire to prepare for recovery operations and reviews fundamental physical principles associated with refrigerant handling and recovery. They include the vapor-pressure law for a pure substance, departures from theory at equilibrium conditions, supercritical states, and the behavior of fluid mixtures. The discussion of the last of these subjects focuses on composition diagrams for zeotropic and azeotropic mixtures and on pressure-composition diagrams for refrigerant-lubricant mixtures. Appendices summarize the purity requirements of ARI Standard 700-88, the results of a bench test of the performance of recovery and recycling equipment, and thermodynamic properties of common CFC, HCFC, and HFC refrigerants. [see RDB4672 for original edition in French]

D. Clodic (École des Mines de Paris, France) and F. Sauer (Dehon Services, France), **Results of a Bench Test of the Performance of Refrigerant Recovery and Recycling Equipment,** paper DE-93-11-5, *Transactions* (Annual Meeting, Denver, CO, June 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASH-

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RAE), Atlanta, GA, 99(2):834-840, 1993 (7 pages with 6 tables, RDB3632)

D. Clodic (École des Mines de Paris, France) and F. Sauer (Dehon Services, France), **Vade-Mecum de la récupération des CFC** [Handbook of CFC Recovery], PYC Édition, Paris, France, 1992 (in French, RDB4672)

[see RDB4673 for abstract of English language edition]

J. P. Doyle (National Refrigerants, Incorporated, NRI), **Refrigerant Management: Conserving a Valuable Resource**, *Heating/Piping/Air Conditioning Engineering* (HPAC), 65(3):59-62, March 1993 (4 pages with 2 figures and 2 tables, RDB3413)

explains the need for a systematic, long-term approach to managing existing refrigerant resources to ease conversions to alternative refrigerants

M. G. Garst (Lennox Industries, Incorporated), **Recovery, Recycling, and Reclamation Guidelines when Servicing Unitary Air-Conditioning and Heat Pump Equipment**, paper DE-93-11-2, *Transactions* (Annual Meeting, Denver, CO, June 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(2):825-828, 1993 (4 pages, RDB3629)

D. P. Grob (Underwriters Laboratories, Incorporated), **Refrigerant Blends - Technical Considerations of Recovery and Recycle of Refrigerants in Mobile Air Conditioning Systems**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 153-162 (repeated on pages 413-422), November 1997 (10 pages with 4 figures, RDB8340)

potential requirements and technical considerations for recovery and recycling of blends to replace R-12 in mobile air-conditioning (MAC) systems

Y. Z. R. Hu, C. H. Chang, C. Y. Yang, and C. C. Chung (Industrial Technology Research Institute, ITRI, Taiwan), **The Development of CFC-Refrigerant, Recovery, Recycling and Reclamation Equipment in ITRI, Taiwan,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 473-481, October 1995 (9 pages with 5 figures and 5 tables, available from JMC as RDB5B16)

R-11 and R-12 recovery, ODS phaseout schedule, R-12 usage in Taiwan

Y. Ishii (Hitachi America Limited, USA), T. Hasegawa, Y. Takamura, and S. Tamata (Hitachi Limited, Japan), **CFC Collection Systems for Refrigerant and Insulation Foam and CFC Decomposition System**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 163-166 (repeated on 423-426), November 1997 (4 pages with 11 figures, RDB8341)

describes a pilot plant for recovery and destruction of chlorofluorocarbons (CFCs) from appliances: removal of R-12 refrigerant and R-11 foam blowing agent from retired refrigerators; catalytic decomposition process; illustration and specifications for a transportable, modular plant

P. G. Johansing, Jr. (Transformation Technologies, Limited), **Chemical and Process Description for Production of High Purity Calcium Halides by Transformation of Halogenated Hydrocarbon Gases**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 500-507, October 1995 (8 pages with 1 figure, available from JMC as RDB5B19)

refrigerant disposal

R. E. Kauffman (University of Dayton Research Institute), **Sealed-Tube Tests of Refrigerants from Field Systems Before and After Recycling**, paper DE-93-11-3 (683-RP), *Transactions* (Annual Meeting, Denver, CO, June 1993), American Society of Heating Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(2):414-424, 1993 (11 pages with 2 figures and 5 tables, RDB3630)

R. E. Kauffman (University of Dayton Research Institute), **Chemical Analysis and Recycling of Used Refrigerant from Field Systems**, paper 3555 (601-RP), *Transactions* (Winter Meeting, Anaheim, CA, January 1992), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 98(1):128-136, 1992 (9 pages with 4 figures and 1 table, RDB2429)

This paper summarizes research to identify and quantify the typical contaminant levels in used refrigerants. A total of 39 samples were taken from both normally operating and failed air-conditioning and refrigerating systems. These samples included R-11 from centrifugal chillers, R-12 from commercial refrigeration systems, R-22 from unitary heat pumps and air conditioners, and R-502 from low-temperature frozen food cases. Results are summarized for measurement of water content (Karl Fisher technique), acid content (ASTM 664 tests), ion content (ion-specific electrode), high-boiling content (gravimetric technique, gas chromatography, and mass spectrography), particulate content (direct-current plasma emission spectrometer and scanning electron microscope), and volatile impurity content (gas chromatography and mass spectrometry). The contaminant levels found exceeded those of new refrigerants, but the types and concentrations varied by refrigerant, application, and whether a system burnout had occurred. Laboratory tests evaluated a recycling scheme based on oil separation followed by water and acid removal, by an alumina/molecular sieve filter/dryer. The preliminary study showed that this recycling procedure is effective in removing acids, but has insignificant effects on volatile impurities and high-boiling residue. The effects of noncondensable gases were not addressed.

K. W. Manz and A. J. Manz (Robinair Division of SPX Corporation), **Efficient Operation of Filter Driers in Refrigerant Recycling Equipment**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:906-913, 1995 (8 pages with 8 figures and 2 tables, rdb7929)

use of in-situ mass flow meters to measure R-12, R-22, R-134a, R-407C, and R-502 in processing through single-pass, distillation recycling machines: model with corrections for superheat and compressor dead volume to determine the refrigerant type from pressure-temperature curves for both single- and two-phase flow

F. Sauer (Dehon Services, France), **Recovery and Containment of Refrigerants in France**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:991-997, 1995 (7 pages with 2 figures, rdb7936)

refrigerant recovery regulations and results; statistics of chlorofluorocarbon (CFC) use by sector in 1986 and 1993 as well as recovery by charge size in 1994; refrigerant fraction of CFC use increased from 9.64 to 29.65% of the totals; nearly half of recovered refrigerants came from systems using 10-50 kg (22-110 lb)

S. Snyder (Robinair Division of SPX Corporation), J. Willis (Asoma Instruments, Incorporated), R. Tobias (Hitek Hardware, Incorporated), and K. W. Manz (Robinair Division of SPX Corporation), **Portable Refrigerant Identification by Near Infrared Spectrophotometry**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 115-120, July 1994 (6 pages with 4 figures and 2 tables, RDB4814)

S. Snyder and K. W. Manz (Robinair Division of SPX Corporation), **Determination of Refrigerant Type Using Vapor Thermal Conductivity Measurements of a Controlled Vapor Sample,** paper DE-93-11-4 (683-RP), *Transactions* (Annual Meeting, Denver, CO, June 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(2):829-833, 1993 (5 pages with 4 figures and 2 tables, RDB3631)

M. Suzuki (Clean Japan Center, Japan), T. Abe, A. Kobayashi, K. Imoto (Nippon Steel Corporation, Japan), T. Amano, H. Komaki (JEOL Limited, Japan), Y. Kawaguchi (Tokyo Electric Power Company, TEPCO, Japan), C. Ohyama (Ichikawa Kankyou Engineering Company, Limited, Japan), T. Takaichi (Japan Fluorocarbon Manufactures Association, Japan), and K. Mizuno (National Institute for Resources and Environment, Japan), **Chlorofluorocarbons (CFCs) Destruction Technology by Induction Coupled Plasma**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 490-499, October 1995 (10 pages with 6 figures and 4 tables, available from JMC as RDB5B18)

describes development of a commercial-scale plant to destroy CFC refrigerants using plasma decomposition technology, already used to dispose of more than 15 tonnes of R-12 recovered from old refrigerators

G. Zehl, J. Freiberg, and M. Meinke (Institute of Environmental Research, Germany), **Environmentally Safe Disposal of Ozone-Depleting CFCs**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 167-175, November 1997 (9 pages with 3 figures and 2 tables, RDB8342)

catalytic reactions for conversion of recovered R-12 and R-22 to R-32 and R-115 to R-125; catalytic process for purification of these hydrofluorocarbons (HFCs) to assure near complete dechlorination

Code of Practice for the Reduction of Chlorofluorocarbon Emissions from Refrigeration and Air Conditioning Systems (Code de Pratique Visant la Réduction des Émissions de Chiorofluorocarbures des Systèmes de Réfrigération et de Conditionnement d'Air), code of practice EPS 1/RA/1, Environment Canada, Ottawa, Ontario,

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Canada, March 1991 (76 pages with 2 tables, in English and French, RDB3505)

This code provides guidelines for reduction of atmospheric emissions of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) used in refrigeration and air-conditioning applications. It covers residential, commercial, and industrial refrigeration, heat pumps, and air conditioning, including mobile air conditioning. The code addresses design, manufacture, installation, servicing, use, recovery, handling, storage, disposal, and training. Three standards recommended by the Society of Automotive Engineers (SAE) are appended. They include *Recommended Service Procedure for the Containment of R-12* (J1989), *Extraction and Recycle Equipment for Mobile Automotive Air-Conditioning Systems* (J1990), and *Standard for Purity of Used Refrigerant in Mobile Air-Conditioning Systems* (J1991). A list of widely-used refrigerants, with chemical names, formulae, and ozone depletion potentials (ODPs) also is appended.

Containers for Recovered Fluorocarbon Refrigerants, ARI Guideline K-1990, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1990 (10 pages, available from ARI for $15.00, RDB3102)

This document provides recommendations for voluntary use by those who supply, use, store, or transport containers for recovered fluorocarbon refrigerants. It is intended as a guide of good practice to facilitate recovery, recycling, and reclamation of refrigerants, to in turn reduce environmental impacts. The need for containers designed and identified specifically for these uses stems from practical and safety considerations. The guideline identifies mandatory federal requirements in the United States, but it is neither an exhaustive listing nor does it address local requirements. It covers cylinders and ton tanks for R-12, R-22, R-114, R-500, and R-502 as well as drums for R-11 and R-113.

Electrostatic Removal of Oil, Water, and Other Contaminants from Refrigerant Flows, proposed research project 998-URP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, in planning (ASH-0998)

The project is being evaluated by ASHRAE Technical Committee 3.3, *Contaminant Control in Refrigerating Systems*. Further information is available from the ASHRAE Manager of Research (+1-404/636-8400).

Handling and Reuse of Refrigerants in the United States, Industry Recycling Guideline IRG-2, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, December 1994 (16 pages with 1 figure and 1 table, available from JMC as RDB5133)

This manual provides procedures and guidelines to maintain the quality of refrigerants used in air-conditioning and refrigeration (ACR) equipment. It defines the terms "recover," "recycle," and "reclaim" and then identifies three options for refrigerant reuse. They include reuse of the refrigerant - without recycling - in the equipment from which it was removed, recycling the refrigerant into the system same or another system from the same owner, or reclaim of the refrigerant. Five considerations are discussed as a basis for selecting the appropriate action. They include the reason the system is being serviced, condition of the refrigerant and system, equipment manufacturers' policies, refrigerant cleaning capability of recycling equipment, and feasibility and owner's preference. A flow chart diagrams the decision process. The document indicates that used refrigerants shall not be sold, or used in a different owner's equipment, unless the refrigerant has been analyzed and found to meet the requirements of ARI Standard 700, "*Specifications for Fluorocarbon and Other Refrigerants*." The document also provides a table of maximum contaminant levels for recycled refrigerants in the same owner's equipment, and notes that the owner's consent should be obtained for such reuse. It provides guidance for identification and avoidance of mixed refrigerants (other than manufactured blends) as well as handling of blends with compositions that were altered by selective leakage. This guideline was developed by a broad base of interests, including refrigerant reclaimers, manufacturers, contractors, engineers, government, building owners and managers, and consumers. It responds to a mandated sunset provision in regulation of reused refrigerants. The underlying goal is indicated as protection of end users, consumers, and ACR products owned by consumers.

Refrigerant Recovery/Recycling Equipment, standard 740-1993, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1993 (20 pages with two figures and 4 tables, available from ARI for $15.00, RDB4944)

This standard establishes uniform methods of testing for rating and evaluating performance of equipment for refrigerant recovery and/or recycling. It addresses contaminant or purity levels, capacity, speed, and purge loss, the last to minimize emission into the atmosphere of refrigerants. The standard is intended for guidance of the industry, including manufacturers, refrigerant reclaimers, repackagers, distributors, installers, servicemen, contractors, and consumers. The refrigerants covered include R-11, R-12, R-13, R-22, R-113, R-114, R-123, R-134a, R-500, R-502, and R-503. It does not apply to zeotropic mixtures of these or other refrigerants. The standard covers general equipment requirements, specifies standard samples for testing, and outlines test apparatus. It prescribes a performance testing procedure, sampling and chemical analysis methods, performance calculations and rating, tolerances, and product labeling. The rating sample characteristics include contents of moisture, particulates, acids, mineral oil, and noncondensable gases. Schematic diagrams show the test apparatus for self-contained equipment and the configuration of a standard air-conditioning or refrigeration system for use as a test apparatus. An appendix specifies the particulate material to be used in standard contaminated refrigerant samples. Conformance with the standard is voluntary, but conformance may not be claimed unless all requirements of the standard are met.

Sealed-Tube Tests of Refrigerants from Field Systems Before and After Recycling, research project 683-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1991 - ongoing (ASH0683)

This project will quantify typical contaminant levels in refrigerants after oil separation, filtering, and drying. It also will determine the effects of contaminants at the concentrations found. The focus is on R-11 from centrifugal chillers, R-12 from commercial refrigeration systems, R-22 from unitary heat pumps, and R-502 from low-temperature commercial refrigeration systems. The work is an extension of ASHRAE research project 601-RP and is being performed by the same contractor, the University of Dayton Research Institute led by R. E. Kaufman. It is sponsored by ASHRAE Technical Committee 3.3, *Contaminant Control in Refrigerating Systems.*

Reducing Emission of Fully Halogenated Refrigerants in Refrigeration and Air-Conditioning Equipment and Systems, ASHRAE Guideline 3-1996, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1996 (available from ASHRAE for $16 to members and $23 for others; RDB7716)

This guideline recommends practices and procedures to reduce inadvertent releases of refrigerants during manufacture, installation, testing, operation, maintenance, and disposal of refrigeration and air-conditioning equipment and systems. It also covers refrigerant recovery, recycling, reclaim, and disposal.

Retrofit and Conversion

N. E. Carpenter (ICI Chemicals and Polymers, Limited), **Retrofitting HFC-134a into Existing CFC-12 Systems,** *International Journal of Refrigeration* (IJR), 15(6):332-339, July 1992 (8 pages, RDB3739)

R-12, R-134a

R. L. Hall (Battelle) and M. R. Johnson (U.S. Air Force), **Alternatives to Ozone Depleting Refrigerants in Test Equipment,** *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 183-189, July 1994 (7 pages with 1 figure and 2 tables, RDB4825)

This paper describes initial results of equipment retrofits to use hydrofluorocarbon (HFC) refrigerants. The equipment included environmental chambers, ultralow temperature freezers, coolant recirculators, a temperature control unit, a vapor degreaser, and a refrigerant recovery system. The conversions entailed replacement of R-12 and R-500 with R-134a, R-13 and R-503 with R-23, and R-502 with R-404A. The mineral oil lubricants were replaced with polyolesters, including Mobil EAL Arctic® 22 CC, ICI Emkarate™ RL 32S, and Castrol Icematic® SW32 based on recommendations of the compressor manufacturers; CPI Solest® LT-32 was used with R-23. The paper outlines the refrigerants used, considerations in selecting alternatives and associated lubricants, concerns with materials compatibility, and the conversions steps followed. The paper indicates that system capacities and power requirements remained virtually unchanged, but that minimum operating temperatures increased slightly in some conversions, notably by 7 °C (12 °F) when replacing R-503 with R-23.

Field Conversion/Retrofit of Products to Change to an Alternative Refrigerant - Construction and Operation (first edition), standard 2170, Underwriters Laboratories Incorporated (UL), Northbrook, IL, 17 September 1993 (20 pages with 2 tables, RDB3B06)

This standard contains requirements for safety engineers to evaluate the construction and operation of air conditioning and refrigeration equipment intended for field conversion/retrofit to an alternative refrigerant. The equipment covered include, but are not limited to, remote commercial refrigerators and freezers, unit coolers, condensing units, split-system central cooling air conditioners and heat pumps, and self-contained equipment. The self-contained group includes commercial refrigerators and freezers, ice makers, ice cream makers, room air conditioners, central cooling air conditioners, heat pumps, and liquid chillers. The standard

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sets out its scope, supplementary requirements, and general requirements for components. It also provides a glossary of terminology used and clarifies the applicable units of measurement and versions of referenced documents. It then specifies requirements relating to the construction of the refrigerating system, refrigerants, design pressures, parts subject to pressure, remote condensers and evaporators, pressure-limiting devices, and pressure relief devices. It also prescribes operational tests for unitary and self-contained equipment and for other equipment types. It concludes with requirements for identification including marking of retrofit equipment and possible notification of the authority having jurisdiction. A table specifies the minimum design pressures for the low-pressure side at 27 °C (80 °F) and high side at 41 and 52 °C (105 and 125 °F). It covers R-11, R-12, R-13, R-13B1, R-14, R-21, R-22, R-23, R-113, R-114, R-115, R-123, R-124, R-125, R-134a, R-C318, R-401A, R-401B, R-402A, R-402B, R-500, R-502, R-503, R-744 (carbon dioxide), and R-764 (sulfur dioxide). A second table specifies minimum wall thickness for steel tubing and for protected and unprotected copper tubing, from 6-67 mm (1/4 - 2-5/8").

Field Conversion/Retrofit of Products to Change to an Alternative Refrigerant - Insulating Material and Refrigerant Compatibility (first edition), standard 2171, Underwriters Laboratories Incorporated (UL), Northbrook, IL, 17 September 1993 (16 pages with 1 table, RDB3B07)

This standard contains test procedures to evaluate the compatibility of an alternative refrigerant with hermetic motor insulating materials and lubricants, for air conditioning and refrigeration equipment intended for conversion/retrofit to an alternative refrigerant. The equipment covered include, but are not limited to, remote commercial refrigerators and freezers, unit coolers, condensing units, split-system central cooling air conditioners and heat pumps, and self-contained equipment. The self-contained group includes commercial refrigerators and freezers, ice makers, ice cream makers, room air conditioners, central cooling air conditioners, heat pumps, and liquid chillers. The standard sets out its scope, supplementary requirements, and general requirements for components. It also provides a glossary of terminology used and clarifies the applicable units of measurement and versions of referenced documents. It then specifies three alternative performance requirements to determine the compatibility of an alternative refrigerant with materials used in the refrigerating system. The first entails testing in accordance with UL Standard 984 or CSA Standard C22.2. The second involves tests by compatibility exposures. The third allows investigation by accepted safety test methods judged equivalent to the preceding two options and that contain specific pass/fail criteria. The remainder of the standard prescribes tests for compatibility exposures, with primary attention to motor insulating materials and motorettes. Required tests are tabulated for magnet wire, helical coils, sheet insulation, lead wire, tie cord, sleeving, tapes, and motorettes. The tests include visual inspection, percent elongation, bond strength, dielectric breakdown, burnout strength, tensile properties, and voltage withstood. The number of samples and test (acceptance) criteria are indicated.

Field Conversion/Retrofit of Products to Change to an Alternative Refrigerant - Procedures and Methods, standard 2172, Underwriters Laboratories Incorporated (UL), Northbrook, IL, 17 September 1993 (RDB3B08)

Forane® Retrofit Training Guide, Elf Atochem North America, Incorporated, Philadelphia, PA, undated circa 1993 (68 pages with 6 tables, available from JMC as RDB4772)

This manual provides a training guide on key issues and procedures associated with refrigerants that affect the air-conditioning and refrigeration industry. It begins with an update on regulations governing the phase out of chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants. It summarizes phaseout schedules under the Clean Air Act Amendments (CAAA) of 1990 for the United States and under the Montreal Protocol. A table indicates the CFC production reduction steps under the original Protocol, 1992 Copenhagen amendments, and CAAA. The document also summarizes CAAA and Protocol deadlines for related actions to reduce emissions of ozone-depleting substances. It then summarizes regulations for refrigerant handling and guidelines and standards associated with refrigerants. Those addressed include Underwriters Laboratories (UL) Guideline 2154 on equipment retrofit, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 15 on safety for mechanical refrigeration, and the Society of Automotive Engineers (SAE) J Standards that give guidelines for automotive applications. The manual then identifies Atochem's refrigerants and presents refrigerant management options. It provides suggestions for promoting retrofits, and discusses factors influencing justifications. The document then discusses lubricants for alternative refrigerants and tabulates the suitability of mineral oil, alkylbenzene, polyalkylene glycol, and polyolester lubricants for common and alternative refrigerants. It describes lubricant flushing procedures and provides a table on residual levels of mineral oil, based on starting concentrations and the number of flushes. The document presents terminology and designations for refrigerants, control and accessory compatibility, and desiccant compatibility. A table shows the suitability of UOP 4A-XH-5, 4A-XH-6, XH-7, and XH-9 molecular sieves with R-11, R-12, R-22, R-32, R-113, R-123, R-124, R-125, R-134a, R-143a, and R-152a. The document then presents general retrofit procedures for hermetic reciprocating-piston and scroll compressors from R-12 to R-409A and R-502 to R-404A, semi-hermetic reciprocating-piston compressors from R-12 to R-134a and R-502 to R-404A, screw compressors from R-12 to R-134a and R-502 to R-404A, centrifugal chillers from R-12 or R-500 to R-134a and R-11 to R-123, and automotive air conditioners from R-12 to R-134a. Eight appendices outline Atochem's refrigerant reclamation program, provide a glossary of terminology and retrofit checklist, outline the previously named guidelines and standards, and provide tabular data on refrigerant-lubricant system replacements and capacity changes for R-123, R-134a, R-404A, and R-409A. Elf Atochem's product names for the refrigerants are Forane® 11, 12, 22, 123, 134a, 404A (FX-70), FX-10 (408A), FX-56 (409A), 500, and 502.

Guide for the Field Conversion/Retrofit of Products to Change to an Alternative Refrigerant Using UL 2170-2172, Underwriters Laboratories Incorporated (UL), Northbrook, IL, 17 September 1993 (10 pages, available from JMC as RDB3B09)

Moving to Alternative Refrigerants: Ten Case Histories - Comfort Coolers, Industrial Process, and Commercial Refrigeration, report EPA 430-K-93-002, U.S. Environmental Protection Agency (EPA), Washington, DC, November 1993 (40 pages, available from JMC as RDB4141)

Appliances

M. J. P. Janssen, F. L. M. Engels (Re/genT BV, The Netherlands), and L. J. M. Kuijpers (Technical University Eindhoven, The Netherlands), **The Use of HFC-134a with Mineral Oil in Hermetic Cooling Equipment**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:860-867, 1995 (8 pages with 5 figures and 3 tables, rdb7922)

use of hydrocarbons as additives in domestic freezers and refrigerator-freezers to convert from R-12 to R-134a with continued use of the original mineral oil as the lubricant: examines R-E170 (dimethyl ether), R-290 (propane), R-C270 (cycloropane), R-600 (n-butane), R-600a (isobutane), R-601 (n-pentane), and R-601a (isopentane); plots show the loss of volumetric cooling capacity and temperature glide with addition of 0-10% hydrocarbons by mass; experimental retrofits of an upright freezer and a refrigerator-freezer from R-12 to R-134a/600a (92/8) and to R-134a; whereas lubrication problems were encountered without hydrocarbon addition freezer, but not with the refrigerator-freezer; no operating problems were encountered with the R-134a/600a blend, though efficiency dropped by approximately 9%; compressor durability and wear tests are underway; authors conclude that use of R-134a/600a is a viable retrofit option and also may be an option for new equipment; potential flammability of the blend or its worst case of fractionation is not addressed

Air Conditioners and Heat Pumps

J. M. Corberán, J. Gonzálvez (Universidad Politécnica de Valencia, Spain), B. Palm, O. Pelletier, and E. Granryd (Kungliga Tekniska Högskolan, KTH, Sweden), **A Numerical Procedure to Estimate the Performance of Heat Pumps when Retrofitted to Alternative Working Fluids,** *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 7, May 1999 (12 pages with 13 figures and 5 tables, RDB9840)

R-22, R-290 (propane)

B. S. Lunger, K. A. Geiger, T. L. Anglin, and S. Narayaman (DuPont Fluoroproducts), **Heat Pump / Air Conditioner Field Test Data for an HCFC-22 Alternative Containing HFC-32, HFC-125, and HFC-134a**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 25-30, July 1994 (6 pages with 5 tables, RDB4805)

R-407C [R-32/125/134a (23/25/52)], Suva® 9000 (formerly AC9000)

O. R. Nielsen (DTI Energy, Denmark) and J. Schreiber (Schreiber Køleteknik A/S, Denmark), **Propane as Refrigerant in Commercial Refrigerating - An Example in Practice**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:933-938, 1995 (6 pages with 1 figure, rdb7932)

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conversion of a system from R-22 to R-290 in a direct-expansion, air-conditioning system; Danish regulations and safety measures

Chiller

A. M. Bell (McQuay International, then SnyderGeneral Corporation), **How to Convert CFC-12 Chillers to HFC-134a**, *Heating/Piping/Air Conditioning Engineering* (HPAC), 65(4):39-42, April 1993 (4 pages with 3 figures, RDB3457)

provides guidance on conversion of centrifugal chillers from R-12 to R-134a

E. M. Clark, G. G. Anderson, and W. D. Wells (DuPont Chemicals), **Retrofitting Existing Chillers with Alternative Refrigerants,** *ASHRAE Journal*, 33(4):38-41, April 1991 (4 pages with 1 table, RDB-5549)

R-123, R-134a, conversion, performance, compatibility

E. D. Lawler, **HFC-134a vs R-12 Centrifugal Chiller Performance Comparison**, McQuay International (then SnyderGeneral Corporation), Staunton, VA, 22 August 1990 (1 page with 1 table, available from JMC as RDB0801)

The performance of a 100-ton, single-stage, hermetic centrifugal water chiller is compared for R-12 and R-134a. Both tests were run at standard rating conditions (ARI Standard 550-88) with the chiller operating at its maximum capacity. The compressor gears were changed to increase the impeller speed to accommodate the greater isentropic head rise required with R-134a. The low-pressure cut-out switch and thermostatic expansion valve were adjusted after changing refrigerants, but other hardware and control settings were the same for both tests. The capacity and efficiency increased with R-134a, by 0.8 and 4%, respectively.

E. D. Lawler, **HFC-134a vs R-500 Centrifugal Chiller Performance Comparison**, McQuay International (then SnyderGeneral Corporation), Staunton, VA, 29 August 1990 (1 page with 1 table, available from JMC as RDB0802)

The performance of a 112-ton, single-stage, hermetic centrifugal water chiller is compared for R-500 and R-134a. Both tests were run at standard rating conditions (ARI Standard 550-88) with the chiller operating at its maximum capacity. The chiller initially was tested with R-500 as a baseline and then recharged with R-134a. The lubricant was changed from a naphthenic mineral oil (Witco Suniso® 4GS) to an ester (Mobil XRL 1681-1). The low-pressure cutout switch and thermostatic expansion valve were adjusted after changing refrigerants, but other hardware and control settings were the same for both tests. A third test was run with the impeller replaced to provide higher flow. The compressor gears were changed for a fourth test to increase the impeller speed. The capacity with R-134a decreased by 9.9, 1.3, and 4.1% for the three tests and the efficiency decreased by 2.8 and 0.5% for the second and fourth tests, but increased by 0.1% for the third.

W. A. Phillips (York International Corporation), **Refrigerant Retrofits: An Overview,** *Heating/Piping/Air Conditioning Engineering* (HPAC), 65(4):33-37, April 1993 (5 pages with 7 figures, RDB3456)

provides guidance on retrofit of centrifugal chillers; discusses levels of conversions and outlook for R-11 and R-12 supplies

B. Seibert (The Trane Company), **How to Convert CFC-11 Chillers to HCFC-123**, *Heating/Piping/Air Conditioning Engineering* (HPAC), 65(4):45-50, April 1993 (6 pages with 5 figures, RDB3458)

provides guidance on retrofit of R-11 centrifugal chillers to R-123

S. G. Sundaresan and R. W. Griffith (Copeland Corporation), **Retrofitting CFC-12 and R-502 Commercial Refrigeration Equipment,** unpublished presentation at the International CFC and Halon Alternatives Conference, Washington, DC, 30 September 1992 (4 pages with 1 figure and 2 tables, available from JMC as RDB4306)

This paper outlines an approach for retrofit of commercial equipment from R-12 or R-502 to either a hydrochlorofluorocarbon (HCFC) or HCFC blend or to a hydrofluorocarbon (HFC) or HFC blend alternative. The paper identifies three verification areas before retrofit: 1) performance, leaks, required oil level, refrigerant-lubricant color and acidity, and operation, 2) materials compatibility, and 3) regulatory compliance and safety approvals. It then discusses refrigerant properties to assure suitability. It suggests that manufacturers be consulted to determine the proper refrigerant charge and operating parameters. The paper discusses considerations for lubricant selection and again recommends consultation with the compressor manufacturer, to determine both selections and cleaning procedures. It reviews typical procedures and provides data from five case histories, to illustrate residual mineral oil concentrations for 1-5 flushes. The authors conclude that retrofit can be successful if recommended procedures are followed; that pending further retrofit experience, sampling and analysis of refrigerants and lubricants is recommended; that knowledge of prior service history is a key requirement; and that shortcuts should be avoided. Tables summarize available refrigerants and lubricants for retrofits.

Retrofitting CFC 12 Systems with Klea™ 134a and Emkarate RL Synthetic Lubricants, ICI Americas Incorporated, New Castle, DE, undated circa 1992 (6 pages with 2 tables, available from JMC as RDB3907)

This document provides information to assist equipment manufacturers and system owners in the conversion of R-12 systems to R-134a. It is based on a comprehensive program of refrigerant and lubricant compatibility studies. The document reviews reasons why R-134a is an important retrofit candidate. They include extension of equipment life beyond the phase out date of R-12, thermodynamic similarity of these two fluids, economic advantages as R-12 costs rise, and avoidance of replacement or conversion delays when R-12 shortages occur. The document reviews lubrication, system modifications, and system chemistry as considerations in retrofits. It then discusses lubrication reliability, compressor reliability, system cooling performance, and energy efficiency after retrofit. The document briefly summarizes two case studies. The first involved a 300 ton SnyderGeneral McQuay centrifugal chiller, from R-500 and mineral oil to R-134a and an ester based lubricant, without a gear change. The capacity decreased by 15.4%, but could be increased with a change in impeller speed. The efficiency improved slightly. The second study involved a large heat pump in Hammarby (Stockholm) Sweden, also from R-500 to R-134a. With changes to the centrifugal compressor, the retrofit system is proving to be at least as efficient with R-134a. The document concludes with a tabular comparison of R-12 and R-134a properties.

Suva® 123 in Chillers, document ART-2 (H-42443-2), DuPont Chemicals, Wilmington, DE, January 1995 (6 pages with 5 tables, RDB7213)

This bulletin discusses use of R-123 in new and retrofit chillers. It briefly introduces R-123 as one of the alternatives to replace chlorofluorocarbon (CFC) refrigerants and specifically R-11. A table compares the boiling point, flammability, exposure limit, ozone depletion potential (ODP), and halocarbon global warming potential (HGWP) for R-11 and R-123. The bulletin identifies general considerations for chiller conversions, indicating that alternative refrigerants cannot simply be "dropped into" systems designed for CFCs. Comparative ranges are provided for capacity, coefficient of performance (COP), evaporator and condenser pressures, and discharge temperature for R-123 relative to R-11. The usual changes in capacity and COP are indicated as -5 to -20% and 0 to -5%, respectively. The bulletin then outlines chemical compatibility considerations, and illustrates differences with a table comparing R-11 and R-123 compatibility with plastics, after exposures at 24 and 54 °C (75 and 130 °F). They include ABS polymer (USS Chemicals Krylastic®), acetal resin (DuPont Delrin®), acrylic (ICI Americas Lucite®), fluorocarbon polytetrafluoroethylene (PTFE, DuPont Teflon®), polyamide 6/6 nylon (DuPont Zytel®), polycarbonate (General Electric Lexan®), polyethylene HD (Oxy Petrochemicals Alathon®), polypropylene (Oxy Petrochemicals Alathon®), polystyrene (Dow Chemical Styron®), and polyvinyl chloride (PVC). A separate table provides length (swell) and weight change data for elastomers following exposures for 7 days at 54 °C (130 °F). Covered polymers include butyl rubber, chlorosulfonated polyethylene (DuPont Hypalon®), fluoroelastomer (DuPont Viton® A), hydrocarbon rubber (DuPont Nordel®), natural rubber, neoprene, neoprene (NBR, Buna N, and SBR, Buna S), polysulfide (Morton Thiokol® FA), silicone, and urethane (Uniroyal Adiprene® C). The bulletin also discusses compatibility with metals and lubricants, noting that those currently used with R-11 are fully miscible with R-123 for expected conditions. It cites stability tests with metals, including steel 1010, copper, and aluminum; the tabulated findings show that R-123 is more stable than R-11. The bulletin then outlines factors for chiller retrofit from R-11 to R-123. It notes that requirements may range from a minimum effort, such as lubricant replacement, to significant changes, such as replacing gears, impellers, or materials of construction. The document then describes a retrofit program, with major equipment manufacturers, to convert DuPont's large chillers from CFCs to alternative refrigerants. It reviews field experience with three case histories, the first involving retrofit of a 1670 kW (475 ton), York open-drive chiller converted to R-123 in September 1988. Monitoring and refrigerant and lubricant sampling are described, along with measurements of machine room concentrations. Typical concentrations of 1 ppm - even during refrigerant removal and recharging - are indicated, with spikes of approximately 8 ppm when making or breaking hose connections. Two other machines at the same site were converted in May/June 1990. The second case history involved conversion of a 3517 kW (1000 ton), Carrier chiller in February 1988. Tests showed 18% loss in capacity, restored with replacement of the impellers at a tradeoff of 15% in efficiency. Measured exposure levels of 1-2 ppm are noted, with spikes as high as 20 ppm during maintenance. A 2110 kW (600 ton), Trane hermetic chiller conversion in October

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1990 also is summarized. The capacity and energy consumption are noted as the same and slightly higher, respectively. Normal machine room concentrations of 1-2 ppm were found; the document discusses the drift in reading encountered with installed infrared monitors. DuPont's product name for R-123 is Suva® 123.

Suva® 134a (Suva Cold MP, HFC-134a) in Chillers, document ART-3 (H-42444-1), DuPont Chemicals, Wilmington, DE, January 1994 (6 pages with 5 tables, available from JMC as RDB4509)

This bulletin discusses use of R-134a in new and retrofit chillers. It briefly introduces R-134a as one of the alternatives to replace chlorofluorocarbon (CFC) refrigerants. A table compares the boiling point, flammability, exposure limit, ozone depletion potential (ODP), and halocarbon global warming potential (HGWP) for R-12 and R-134a. The bulletin identifies general considerations for chiller conversions, indicating that alternative refrigerants cannot simply be "dropped into" systems designed for CFCs. Comparative ranges are provided for capacity, coefficient of performance (COP), evaporator and condenser pressures, and discharge temperature for R-134a relative to R-12. The usual changes in capacity and COP are indicated as -10 to +2% and -8 to +2%, respectively. The bulletin then outlines and tabulates chemical compatibility considerations, and illustrates differences with a table comparing R-12 and R-134a compatibility with elastomers after exposures at 25, 80, and for some 141°C (77, 176, and 285 °F). They include urethane (Uniroyal Adiprene® C), Buna N and S, butyl rubber, chlorosulfonated polyethylene (DuPont Hypalon® 48), natural rubber, neoprene W, hydrocarbon rubber (DuPont Nordel®), silicone, polysulfide (Morton Thiokol® FA), and fluoroelastomer (DuPont Viton® A). The bulletin also discusses lubricants and contrasts polyalkylene glycol (PAG) and polyolester (POE) synthetics to mineral oils (MO). A table indicates the temperature ranges from -50 to 93 °C (-58 to 200 °F) for solubility of R-134a in naphthenic and paraffinic MO, alkylbenzene and dialkylbenzene, two PAGs, and four POEs. The bulletin outlines factors for chiller retrofit from R-12 and R-500 to R-134a. It notes that requirements may range from a minimum effort, such as lubricant replacement, to significant changes, such as replacing gears, impellers, or materials of construction. The document describes a retrofit program, with major equipment manufacturers, to convert DuPont's large chillers from CFCs to alternative refrigerants. It then reviews field experience with a 3460 kW [probably 2460 kW] (700 ton), York International TurboPak® centrifugal chiller, converted to R-134a and an unidentified 300 SUS PAG lubricant in November 1989. Subsequent inspections and a second retrofitting of the drive gear, in the spring of 1990, are described, indicating satisfactory operation with a decrease in efficiency of up to 7% and an increase in capacity of up to 9%. The document also discusses conversion of a Carrier open-drive, R-12 chiller rated at 4224 kW (1200 ton) to R-134a with a PAG in December 1990; the gear set was changed in the spring of 1991. A maintenance problem with the lubricant oil pump and slight wear in the compressor journal bearings were found. While the cause was not ascertained, the lubricant was changed to a POE, indicated as less sensitive to residual chlorides. A third case history involved a 10,560 kW (3000 ton) open drive, York R-500 chiller with naphthenic MO. It was converted to R-134a with a POE in April 1991; preliminary testing confirmed that a gear change was not needed. A fourth was with a 10,560 kW (3000 ton) open drive, Carrier 17DA chiller, for which the external gear set was replaced to increase the speed by 13%. The R-12 and naphthenic MO were replaced with R-134a and a POE in April 1991. The efficiency and capacity were increased, the latter by 7%. A fifth case involved conversion of a 7040 kW (2000 ton) Worthington 52EH chiller, from R-12 and MO to R-134a and POE in July 1992. After overhaul and a speed increase, the capacity and efficiency increased by 2 and 10%, respectively. This case was unique in several respects, since this chiller design is limited in operating pressure and condenser replacement may be required for other machines. Also, the chiller had not been overhauled since its original installation in 1965. The bulletin mentions flushing with R-11 for the first two retrofits and with POE for the remainder. Also, the lubricant viscosity had to be increased in the last two to reduce operating pressures. The bulletin indicates that monitoring is continuing. DuPont's product names for R-134a refrigerant are Suva® 134a and Suva® Cold MP.

Commercial Refrigeration

M. R. Brubaker, G. D. Rolotti, and P. F. Radice (Elf Atochem North America), **Practical Interim Solutions for Existing R-12 and R-502 Installations: Technical Data and Case Studies on R-409A and R-408A,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 225-233, October 1995 (9 pages with 5 figures and 3 tables, available from JMC as RDB5A63)

R-408A, R-409A, lubricant miscibility, flammability, fractionation, efficiency, retrofit, vending machine, commercial ice maker

J. J. Byrne, M. Shows, and M. W. Abel (Integral Sciences, Incorporated, ISI), **Investigation of Flushing and Clean-Out Methods for Refrigeration Equipment to Ensure System Compatibility**, report DOE/CE/23810-73, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 24 April 1996 (68 pages with 2 figures and 17 tables, available from JMC as RDB6C03)

This report assesses procedures to remove contaminants from refrigeration systems. It compares methods for mineral oil removal, for conversion of R-12 systems to use R-134a, including "triple-flush" approaches, variants thereof, and flushing with terpenes. The report also surveys process alternatives to clean motor burnouts, in systems using hermetic and semi-hermetic compressors. It then reviews criteria for flushing- and cleaning-solvent selection. Advanced methods, including use of polyolester (POE) cosolvents, alkylbenzene lubricants, flushing with R-22, and cleaning with the original R-12 charge are discussed. The report describes a 12 kW (3 ton) system, employing a bolted hermetic reciprocating-piston compressor, and a system serving a supermarket dairy-case. These systems were used for laboratory and field comparisons of the flushing methods for R-134a retrofits. Data are tabulated to compare lubricant removal, costs, and material requirements for triple-flush and alternative methods. Two appendices summarize difficulties with solvent evaporation and provide an annotated bibliography of resource and reference materials. The report concludes that the alternative methods offer considerable reduction in cost and waste.

S. Corr (ICI Chemicals and Polymers, Limited), T. W. Dekleva, and A. L. Savage (ICI Americas, Incorporated), **Retrofitting Large Refrigeration Systems with R-134a**, *ASHRAE Journal*, 34(2):29-33, February 1993 (5 pages with 3 figures and 2 tables, RDB3303)

R-134a, synthetic polyolester (POE) lubricants, retrofit of R-12 systems: overview, capacity change, lubrication, system durability, compatibility, case study in a food processing plant

S. Corr, R. D. Gregson, G. Tompsett (ICI Chemicals and Polymers, Limited), A. L. Savage and J. A. Schukraft (ICI Americas, Incorporated), **Retrofitting Large Refrigeration Systems with R-134a**, *Proceedings of the 1992 International Refrigeration Conference - Energy Efficiency and New Refrigerants,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 1:221-230, July 1992 (10 pages; expanded reprint available from JMC, 14 pages with 7 figures and 1 table, RDB2724)

use of R-134a to retrofit R-12, compatibility tests, flushing procedures, mineral oil tolerance, case study for a refrigeration system in a food processing plant

J. P. Davey and C. C. Mulliss (Rhône-Poulenc Chemicals Limited, UK), **Field Experience in Retrofitting Isceon 134a and Isceons 69-S and 69-L**, *CFC Alternatives: User Experience and Update*, Institution of Mechanical Engineers and Institute of Refrigeration, London, UK, 11 November 1992 (13 pages with 1 figure and 7 tables, available from JMC as RDB3331)

R-134a, R-403A, and R-403B

D. H. Walker, **Medium-Temperature Supermarket Refrigeration Conversion from CFC-12** to **HCFC-22 (R-12 to R-22), report** TR-101265, Electric Power Research Institute (EPRI), Palo Alto, CA, December 1992 (78 pages with 8 figures and 24 tables, RDB3616)

Klea® 60, Replacement for R-502 in New and Existing Equipment, technical note 620250450, ICI Americas Incorporated, Wilmington, DE, October 1993 (8 pages with 3 tables, available from JMC as RDB3A61)

This document describes R-407A, a ternary, zeotropic blend of R-32, R-125, and R-134a (R-32/125/134a), developed as a replacement for R-502 for commercial and transport refrigeration. The technical note summarizes the phase out of chlorofluorocarbon (CFC) refrigerants, the need for alternatives to R-502, and ICI's search for likely replacements. It then compares the atmospheric lifetimes, ozone depletion potentials (ODPs) and halocarbon global warming potentials (HGWPs) of R-22, R-32, R-125, R-134a, R-502, and the R-32/125/134a blend. It also provides a tabular comparison of the physical properties, at the normal boiling point, and theoretical performance between R-502 and the blend. The document then discusses the flammability and toxicity of both the blend and its components, noting that the composition was designed to be nonflammable despite the R-32 content. The bulletin also discusses handling and leakage and states that composition changes are anticipated to be less serious than had been expected. It discusses appropriate lubricants, with focus on the ICI Emkarate® family of synthetic, neopentyl polyolesters. Several documents are cited as available or under preparation to provide thermophysical properties, flammability and toxicity specifics, blend design information, handling and storage advice, and retrofit case studies. ICI's product name for R-407A is Klea® 60.

Klea® 61, Replacement for R-502 in New and Existing Equipment, technical note 620250460, ICI Americas Incorporated, Wilmington, DE, October 1993, reprinted April 1994 (8 pages with 3 tables, RDB3A62)

This document describes R-407B, a ternary, zeotropic blend of R-32, R-125, and R-134a (R-32/125/134a), developed as a replacement for R-502 for commercial and transport refrigeration. It is specifically targeted for R-502 retrofit applications operating at high lift, for example -40 °C (-40 °F) evaporating and 40 °C (105 °F) or higher condensing. It may also be suited for use in hermetic compressors where discharge temperature is a critical parameter. The technical note summarizes the phase out of chloro-fluorocarbon (CFC) refrigerants, the need for alternatives to R-502, and ICI's search for likely replacements. It then compares the atmospheric lifetimes, ozone depletion potentials (ODPs) and halocarbon global warming potential (HGWPs) of R-22, R-32, R-125, R-134a, R-502, and the R-32/125/134a blend. It also provides a tabular comparison of the physical properties, at the normal boiling point, and theoretical performance between R-502 and the blend. The document then discusses the flammability and toxicity of both the blend and its components, noting that the composition was designed to be nonflammable despite the R-32 content. The bulletin also discusses handling and leakage and states that composition changes are anticipated to be less serious than had been expected. It discusses appropriate lubricants, with focus on the ICI Emkarate® family of synthetic, neopentyl polyolesters. Several documents are cited as available or under preparation to provide thermophysical properties, flammability and toxicity specifics, blend design information, handing and storage advice, and retrofit case studies. ICI's product name for R-407B is Klea® 61.

Klea® 407C (Klea® 66), Replacement for HCFC-22, technical note 620250471, ICI Klea Incorporated, Wilmington, DE, January 1995 (12 pages with 2 figures and 3 tables, limited copies available from JMC as RDB6B35)

This document describes and provides data on R-407C, a ternary, zeotropic blend of R-32, R-125, and R-134a [R-32/125/134a (23/25/52)], developed as a replacement for R-22 in new equipment. The technical note summarizes the phase out of chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants, the need for alternatives to R-22, and ICI's search for likely replacements. It then compares atmospheric lifetime, ozone depletion potentials (ODP) and halocarbon global warming potential (HGWP) data for R-22, R-32, R-125, R-134a, and R-407C. It also provides a comparison of physical properties, at the normal boiling point, and theoretical performance comparison between R-22 and the blend. Two plots compare the coefficient of performance (COP) and cooling capacity, for evaporator temperatures of -20 to 10 °C (-4 to 50 °F) for R-22 and the blend. They show the blend's performance to be equal to, or slightly better than that of R-22. The document then discusses the flammability and toxicity of both the blend and its components, noting that the composition was designed to be nonflammable despite its R-32 content. The bulletin briefly reviews handling and leakage. It advises that the blend always should be liquid charged into systems, and that investigation has shown that degradation of performance will not be significant with anticipated leakage. The document next discusses appropriate lubricants, with focus on the ICI Emkarate® RL family of synthetic, neopentyl polyolesters. Several documents are cited as available or under preparation to provide thermophysical properties, flammability specifics, blend design information, handling and storage advice, and retrofit guidance. ICI's product name for R-407C is Klea® 407C (formerly Klea® 66).

Retrofit Changeover Guidelines - CFC-12 to HFC-134a, form 93-04-R1, Copeland Corporation, Sidney, OH, April 1993 (4 pages with 1 table, available from JMC as RDB3714)

R-12 to R-134a

Retrofit Changeover Guidelines - CFC-12 to MP39, form 93-02-R1, Copeland Corporation, Sidney, OH, April 1993 (8 pages with 2 tables, RDB-3715)

R-12 to R-401A

Retrofit Changeover Guidelines - CFC-12 to MP66, form 93-03-R1, Copeland Corporation, Sidney, OH, April 1993 (8 pages with 2 tables, RDB-3716)

R-12 to R-401B

Retrofit Changeover Guidelines - CFC-12 to Suva® HP80, form 93-05, Copeland Corporation, Sidney, OH, June 1993 (8 pages with 2 tables, RDB3717)

R-12 to R-402A

Retrofit Guidelines for Suva® HP62, document ART-22 (H-53019), DuPont Chemicals, Wilmington, DE, January 1994 (8 pages with 2 tables, available from JMC as RDB4510)

This bulletin provides guidance on retrofit of R-502 equipment with R-404A - R-125/143a/134a (44/52/4) - in medium and low temperature refrigeration applications. It briefly reviews the properties and safety of the two refrigerants and provides a table comparing their boiling points, vapor pressures and liquid densities at 25 °C (77 °F), vapor densities at -15 °C (5 °F), ozone depletion potentials (ODP), global warming potentials (GWP), capacities, and efficiencies. The bulletin outlines lubricant selection criteria, and notes that polyolester (POE) lubricants are recommended for most hydrofluorocarbon (HFC) systems. It offers guidance on handling POEs and the impacts of residual mineral oil. The bulletin identifies retrofit modifications, including consideration of compatibility with plastics and elastomers, but notes that minimal changes are anticipated. As for lubricants, it recommends that the materials involved be reviewed with the equipment manufacturer before retrofit. The refrigerant is indicated as suited for use in such applications as food service, commercial refrigeration, and transport refrigeration. The bulletin discusses suitability considerations and provides guidance in choosing among selected retrofit alternatives. It provides an overview of the retrofit process and identifies equipment and supplies needed. An inset notes the conditions under which Copeland Corporation approves the use of R-402A and R-404A and that excess pressure, possibly resulting in an explosion, could result without a properly installed, appropriate pressure relief valve. The bulletin then presents an eight-step retrofit procedure accompanied by a retrofit checklist and system data sheet to facilitate the process. It also provides a pressure-temperature chart, in metric (SI) and inch-pound (IP) units, covering 25-2900 kPa and -71 to 61 °C (-25 to 400 psig and -107 to 140 °F). DuPont's product name for R-404A is Suva® HP62.

Retrofit Guidelines for Suva® HP80, document ART-9 (H-45947-2), DuPont Chemicals, Wilmington, DE, December 1993 (10 pages with 2 tables, available from JMC as RDB4506)

R-402A

Retrofit Guidelines for Suva® HP81, document ART-15 (H-47763-1), DuPont Chemicals, Wilmington, DE, March 1993 (10 pages with 1 table, available from JMC as RDB4507)

R-402B

Retrofit Guidelines for Suva® MP39 and Suva® MP66, document ART-5 (H-42446-4), DuPont Chemicals, Wilmington, DE, October 1996 (12 pages with 4 tables, available from JMC as RDB7214)

This bulletin provides application information for R-401A and R-401B for retrofit use. These alternative refrigerants are identified as service replacements for R-12 and, for the latter, also R-500 in direct expansion systems using positive displacement (reciprocating piston, rolling rotary piston, scroll, and screw) compressors. The bulletin reviews and tabulates representative physical and environmental properties as well as comparative performance for R-12, R-500, R-401A, and R-401 B. The data suggest 8 and 16% higher capacity and slightly higher efficiency, compared to R-12, and comparable efficiency and capacity to R-500. The bulletin then discusses lubricant selection, and recommends use of alkylbenzene lubricants to overcome miscibility concerns with mineral oils. It then discusses filter driers, suggests that they be changed during retrofits, and provides selection guidance for solid core, loose filled, and compacted bead driers. It outlines necessary system modifications with attention to hoses and gasket materials, and cautions against mixing R-401A and R-401B with other refrigerants, including R-12 and R-500, and additives. The bulletin summarizes the equipment, supplies, and procedures needed for retrofit with specific attention to lubricant changes, leak checking, charging, adjustments, and labeling. It also discusses the effects of temperature glide and provides pressure-temperature charts in both inch-pound (IP) and metric (SI) units. The bulletin concludes with discussion of superheat and subcooling, a retrofit checklist, and a system data sheet to record component data and operating parameters. DuPont's product names for R-401A and R-401B are Suva® MP39 and MP66, respectively.

Retrofit Guidelines for Suva® 134a (Suva® Cold MP) in Stationary Equipment, document ART-16 (H-47761-1), DuPont Chemicals, Wilmington, DE, January 1993 (H-47761), revised March 1993 (8 pages with 1 table, available from JMC as RDB3447)

This bulletin provides guidance on retrofit of R-12 equipment with R-134a in commercial refrigeration, air conditioning, medium temperature appliances, and chillers using both positive displacement and dynamic compressors. The bulletin notes that R-134a may be used in lower evaporator temperature applications, but may result in reduced capacity. It cautions that R-134a should not be used in conjunction with other refrigerants, and specifically not added to an R-12 charge, since the mixture can form a high pressure azeotrope that could cause damage. The bulletin outlines lubricant selection criteria, and notes that polyolesters are recommended for most R-134a systems. It offers guidance on handling polyolesters and the im-

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pacts of residual mineral oil. The bulletin identifies retrofit modifications, including consideration of compatibility with plastics and elastomers, but notes that minimal changes are anticipated. It provides an overview of the retrofit process and identifies equipment and supplies needed. It then presents a ten-step retrofit procedure accompanied by a retrofit checklist and system data sheet to facilitate the process. It also provides a pressure-temperature chart in metric (SI) and inch-pound (IP) units covering 25-3600 kPa and -53 to 95 °C (-15 to 300 psig and -40 to 160 °F). DuPont's product names for R-134a are Suva® 134a and Suva® Cold MP.

Heat Pumps for District Heating

K. Berglöf (AKA Kyla AB, Sweden) and A. Bertelsen (Marketing Communications AB, Sweden), **Replacing CFC-12 in the World's Largest Heat Pumps**, *IEA Heat Pump Newsletter - CFC and HFC Replacement*, International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, 13(1):32-34, March 1995 (3 pages with 1 figure, RDB5690)

R-12 to R-134a conversion, Ryaverket, Göteborg, Sweden

T. W. Dekleva (ICI Americas, Incorporated), B. Durr, P. D. Guy (ICI Chemicals and Polymers, Limited, UK), L. Petersson, and T. Widgren (ABB STAL AB, Sweden), **Retrofit of a Swedish District Heat Pump from R-500 to Klea® 134a**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC), Alliance for Responsible CFC Policy, Arlington, VA, 203-210, October 1993 (8 pages with 3 figures and 4 tables, RDB3A43)

R-500 to R-134a

T. Widgren with preface by L. Petersson, **Conversion to HFC-134a in a 25 MW Heat Pump, Hammarby, Sweden**, report RT-IST-51 /92, ABB STAL AB, Finspång, Sweden, September 1992 (28 pages with 13 figures and 2 tables, RDB2B10)

This report summarizes conversion of a large heat pump, for district heating, from R-500 to use of R-134a and the first subsequent year of operating experience. The report reviews both use of large heat pumps in Sweden and corresponding use of refrigerants. It then reviews specific considerations for this conversion, including a description of the heat pump and its two-stage, centrifugal compressor. The thermophysical properties of alternative refrigerants are outlined, with emphasis on projected performance with R-134a. Equipment modifications for the conversion are described, including a summary of compatibility considerations with the new refrigerant and polyalphaoleofin (PAO) lubricant. The conversion, start up, and added refrigerant leak monitors are reviewed. Operational experience for 1991 /1992 is discussed, including capacity, efficiency, availability, refrigerant and lubricant sampling, sealants, and leakage. The report concludes that the conversion was successful. The heat pump ran for 6,641 hours of operation and 148 GWh (0.5 trillion Btu) of production at output temperatures sometimes exceeding 90 °C (194 °F). There were no unplanned outages. Peak capacity is 2-4% lower with R-134a than with R-500, leading to an annual reduction in output of 1.4%. Efficiency is essentially the same. [This conversion is believed to be the largest single use of R-134a to date.]

Industrial Heat Pumps

B. Hivet and C. Gillet Électricité de France, ÉDF, France), **HFC-134a and HCFC-22/142b Mixture for Conversion of CFC-12 Heat Pumps,** *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 159-164, July 1994 (6 pages with 4 figures, RDB4821)

R-134a, R-22/142b

Industrial Refrigeration

D. Arnaud (Elf Atochem S.A., France) and G. D. Rolotti (Elf Atochem North America, USA), **An Example of Successful CFC-12 Retrofit with HFC-134a in the Industrial Field**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC), Alliance for Responsible CFC Policy, Arlington, VA, 193-202, October 1993 (10 pages with 3 figures and 5 tables, RDB3A42)

N. D. Amos, T. Chadderton (Meat Industry Research Institute of New Zealand, MIRINZ), and A. C. Cleland (Massey University, New Zealand), **Performance of a Cold Store R-502 Refrigeration System Retrofitted with the Ozone-Benign R507 Refrigerant**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:727-733, 1995 (7 pages with 1 figure and 1 table, rdb-7914)

evaluation of an industrial refrigeration system retrofit from R-502 with a mineral oil to R-507A with a polyolester (POE, Mobil Arctic® EAL 32) lubricant: two nearly identical, side-by-side systems were instrumented and monitored for 26 days before and 24 days after one of them was converted in a cold-storage warehouse for vegetables; operation was deemed reliable and system efficiency was improved; a fourth lubricant flush was needed and the recommended method to determine oil-mixture composition was found to disagree with a more reliable, refractometer method

Mobile Air Conditioners

B. Abboud, **Field Trials of Propane/Butane in Automotive Air Conditioning**, B.E. thesis (School of Mechanical and Manufacturing Engineering), University of New South Wales, Sydney, Australia, 1994 (300 pages, rdb8368)

performance of R-290/600a in mobile air-conditioning (MAC) systems

M. W. Abel (Integral Sciences Incorporated, ISI), **Flushing Solvent Criteria for Mobile A/C Systems**, conference presentation (Mobile Air Conditioning Society (MACS) Annual Meeting, New Orleans, LA, 28 January 1995); published as paper DOE/CE/23810-56, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, January 1995 (21 pages with 2 figures, available from JMC as RDB5342)

A series of presentation charts outlines an investigation of and criteria for selection of a flushing solvent, for retrofit of mobile air-conditioning (MAC) systems. The cleanout is needed when converting from R-12 with mineral oil to R-134a and a suitable lubricant. A chart identifies seven requirements, namely compatibility with system materials, ease of removal, minimal (ideally zero) ozone depletion potential (ODP), low flammability, low toxicity, cost effectiveness, and ease of recycling and ultimate disposal. Further charts describe flushing procedures using liquid R-12 and terpenes. Others outline the Environmental Protection Agency (EPA) Solvent Alternatives Guide (SAGE), a computer program that suggests replacements for chlorinated solvents based on responses to a series of questions. The SAGE process and chemical alternatives are identified. Presentation comments note that SAGE recommendations manifest a high tolerance for aqueous and flammable solvents as well as those requiring complex methods. The presentation then lists solvent requirements and acceptable solvents under the EPA Significant New Alternatives Program (SNAP). It also discusses observations on commercially-available solvents, noting that they are either aqueous, flammable, have high boiling points, or are unacceptable under SNAP. Of the more than 1000 organic compounds screened, all fail one or more of the ideal requirements. Charts summarize complexities of solvent removal, for example from dead spots in the system and evaporation difficulty. Two plots compare the volume of a fixed weight of 14 solvents, to suggest an index of solvent removal difficulty. They include R-12, R-13I1, R-22, R-113, R-123, R-141b, R-290 (propane), R-502, acetone, and hexane. B-pinene, d-limonene, and water also are included, but shown to be much more difficult to remove.

K. M. Adams (Technical Chemical Company), **Freeze 12® Answering the Call for an Alternative Refrigerant,** *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 397-402, November 1997 (6 pages with 2 figures, RDB8355)

describes a retrofit test of R-134a/142b (80/20) in a mobile air-conditioning (MAC) system converted from R-12 and the marketing and support program for use of this binary zeotrope; concludes that loss of evaporator performance was insignificant and that the compression ratio was reduced

W. Atkinson (Sun Test Engineering), **A Summary of the Mobile A/C Comfort Evaluation - Phoenix Alternate Refrigerant Forum - July 15-18, 1998**, *The Earth Technologies Forum* (proceedings, Washington, DC, 26-28 October 1998), Alliance for Responsible Atmospheric Policy, Arlington, VA, 112-120, October 1998 (9 pages with 12 figures and 3 tables, RDB8B12)

summarizes subjective comfort evaluations of mobile air-conditioning (MAC) systems in on-road conditions for 14 vehicles including 7 using R-134a, 4 using R-744 (carbon dioxide), and 1 using an unidentified hydrocarbon refrigerant; presents findings; discusses differences between road and laboratory (wind tunnel) tests, safety implications, and considerations for future development and use of MAC systems

J. A. Baker (General Motors Corporation), **Mobile Air Conditioning and the Global Climate - A Summary of the Phoenix Alternate Refrigerant Forum - July 15-18, 1998**, *The Earth Technologies Forum* (proceedings, Washington, DC, 26-28 October 1998), Alliance for Responsible Atmospheric Policy, Arlington, VA, 104-111, October 1998 (8 pages with 1 table, RDB8B11)

mobile air-conditioning (MAC) systems: impact of R-134a use on global climate; desired attributes and status of alternatives; indicates that average R-134a needs for current technology systems amount to 2 recharges In a 12 year life with a 0.91 kg (2 lb) charge; projects reduction

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to 1 recharge in a 12 year life with a 0.80 kg (1.8 lb) charge; based on recharge at 40% charge loss with 6% recovery and recycling losses to amount to 125 and 189 kg (276 and 417 lb) carbon dioxide (CO_2) equivalent with and without recovery, respectively, on an annualized basis, or 1.50 and 2.27 metric tonne (t) (3300 and 5000 lb) for the vehicle lifetime for current technology systems; the corresponding emissions for future technologies are projected at 62 and 127 kg (137 and 280 lb) and 0.744 and 1.52 t (1640 and 3350 lb); promotes use of total equivalent warming impact (TEWI) to gauge system effects; presents analyses to estimate budgets for mitigation activities versus purchase of credits through emissions trading; notes that MAC systems using R-744 (CO_2) as a refrigerant are projected to cost 20% more and weigh 2.5 kg more than current R-134a systems

S. Barbusse (ADEME, French Agency for Environment and Energy Management, France), D. Clodic (École des Mines de Paris, France), and J-P. Roumegoux (INRETS, National Research Institute for Transports and their Safety, France), **Mobile Air Conditioning and Simulation of Energy and Fuel Consumptions,** *The Earth Technologies Forum* (proceedings, Washington, DC, 26-28 October 1998), Alliance for Responsible Atmospheric Policy, Arlington, VA, 121-129, October 1998 (9 pages with 9 figures and 4 tables, RDB8B13)

summarizes field and laboratory measurements to estimate fuel use for operation of mobile air conditioning (MAC) systems; provides estimates of MAC penetration in new cars in Europe (30%), France (60%), Japan (>90%), and the USA (>90%); suggests modifications warranting investigation to reduce power requirements and regulatory approaches to reflecting MAC energy consumption

S. H. Colmery, T. W. Dekleva, and C. L. Jarrell (ICI Klea), **Studies on the Condition of Vehicle Air Conditioning Systems - Two Years After Retrofitting HFC-134a**, paper 940599 (SAE International Congress and Exposition, Detroit, MI, 28 February -3 March 1994), Society of Automotive Engineers (SAE), Warrendale, PA, 67-72, 1994 (6 pages, rdb-4A25)

R-134a, mobile air-conditioning (MAC) systems

S. Corr, E. Goodwin, R. D. Gregson, A. Halse, A. Lindley (ICI Chemicals and Polymers, Limited), S. H. Colmery, T. W. Dekleva, and R. Yost (ICI Americas, Incorporated), **Ester Lubricants for Use with HFC-134a Retrofit Applications,** seminar presentation at the Society of Automotive Engineers (SAE) International Congress and Exposition (Detroit, MI), ICI Americas Incorporated, New Castle, DE, 25 February 1992 (22 pages with 23 charts, RDB2619)

This document provides the presentation charts and text for an update on retrofit of mobile air air-conditioning (MAC) systems. The presentation reviews the basis for selection of R-134a including consideration of performance, avoidance of ozone depletion, and safety. The lubricant used is identified as a fundamental issue in retrofitting MAC systems with R-134a. Properties of two candidate esters and sealed-tube test results, including both mineral oil and R-12 as contaminants, are reviewed. One finding is that the lubricants impact the materials examined more than the refrigerants. Volume change (swell) is plotted for R-12 with mineral oil, the same pair followed by R-134a with a polyolester, and R-134a with the ester alone for nine elastomers. They include chlorosulfonated PE, EPDM, EPDM-O, EPDM-S, fluoropolymer, HNBR, natural rubber, neoprene, and nitrile. Compressor tests to examine the suitability of the fluids are summarized; the tests included high contaminant levels to approximate those expected in retrofits. A rating system to gauge wear is outlined. Fleet trials conducted in Australia are summarized, noting anecdotal suggestions that R-134a may provide improved performance. While much more study is needed, the esters tested appear promising for use with R-134a in MAC system retrofit.

D. Q. Darlage (Peoples Welding Supply, Incorporated), B. C. Burke (ATC Specialists), D. Hatton (Monroe Air Tech), J. Burke (United Suppliers of America), and G. H. Goble (GHG Dev Labs, Incorporated), **Profile of Autofrost® Refrigerants,** *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 392-396, November 1997 (5 pages with 1 table, RDB8354)

R-406A [R-22/600a/142b (55/4/41)], R-414A [R-22/124/600a/142b (51/28.5/4/16.5)], R22/-600a/142b (65/4/31), and R-22/227ea/600a/142b (41/40/4/15) identified as GHG-X3 (also Autofrost-X3), GHG-X4 (also Autofrost-X4), GHG-X5, and GHG-HP, respectively; discusses personal views on, circumvention of, and observations regarding current requirements for fittings, recycling, and recovery of refrigerants for mobile air-conditioning (MAC) systems

P. G. Gott, **Automotive Air-Conditioning Refrigerant Service Guide,** Society of Automotive Engineers (SAE), Warrendale, PA, and Mobile Air Conditioning Society (MACS), East Greenville, PA, September 1992 (rdb3735)

This publication details proper service procedures involving refrigerants for automotive air conditioners for service technicians. It addresses issues such as how to avoid refrigerant contamination. It also contains the complete text of Society of Automotive Engineers (SAE) standards applicable to R-12 and R-134a recycling and service. They include "Recommended Service Procedure for the Containment of R-12" (standard J1989), "Standard of Purity for Use in Mobile Air-Conditioning Systems" (J1991), "Standard of Purity for Recycled HFC-134a for Use in Mobile Air-Conditioning Systems" (J2099), "Service Hoses for Automotive Air Conditioning" (J2196), "HFC-134a Service Hose Fittings for Automotive Air-Conditioning Service Equipment" (J2197), "Recommended Service Procedure for the Containment of HFC-134a" (J2211), and "Safety and Containment of Refrigerants" (J639).

Y. Z. R. Hu, C. H. Chang, W. F. Sung, and C. L. Shyu (Industrial Technology Research Institute, ITRI, Taiwan), **Current Development of Retrofitting Mobile Air Conditioning System in Taiwan**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 516-525, October 1995 (10 pages with 5 tables, available from JMC as RDB5B21)

R-12 to R-134a and R-401C, retrofit of automotive air conditioners

J. J. Jetter (U.S. Environmental Protection Agency, EPA) and F. R. Delafield (Acurex Environmental Corporation), **Alternatives for CFC-12 Refrigerant in Automotive Air Conditioning**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 366-374, November 1997 (9 pages with 5 figures and 3 tables, RDB8346)

performance tests of nine retrofit alternatives in a mobile air-conditioner (MAC) converted from R-12: tests at three operating conditions compared the refrigeration capacity, coefficient of performance (COP), compressor discharge pressure, compressor discharge temperature, and evaporator outlet pressure; tested refrigerants included R-12 for reference, R-134a, R-406A, R-22/124/600a/142b (51/28.5/4/16.5) [proposed R-414A] and (50/39/1.5/9.5 [proposed R-414B], R-416A, R-22/600a/142b (65/4/31), R-134a/142b (80/20) and 79/19 with a lubricant additive, and a proprietary blend identified as Ikon-12 [possibly R-152a/13I1 (25/75)]; the COPs and capacities for R-134a were 7-9 and 8-9% lower, respectively than for R-12; blends containing R-22 tended to have higher capacities, but discharge pressures that were 17-34% higher and discharge temperatures as much as 5 °C (9 °F) higher than for R-12; concludes that further laboratory and field testing is needed to adequately evaluate performance, materials compatibility, chemical stability, fractionation, and long-term durability

J. J. Jetter, N. D. Smith (U.S. Environmental Protection Agency, EPA), K. Ratanaphruks, A. S. Ng, M. W. Tufts, and F. R. Delafield (Acurex Environmental Corporation), **Evaluation of Ikon®-12 Refrigerant for Motor Vehicle Air Conditioning,** paper 970525 (SAE International Congress and Exposition, Detroit, MI), Society of Automotive Engineers (SAE), Warrendale, PA, 1997 (rdb8347)

performance tests of a proprietary blend identified as Ikon-12 [possibly R-152a/13I1 (25/75)] in a mobile air-conditioning (MAC) system

A. S. Parmar, **Performance of Hydrocarbon Refrigerants in Motor Car Air Conditioning,** B.E. thesis (School of Mechanical and Manufacturing Engineering), University of New South Wales, Sydney, Australia, 1995 (rdb8370)

performance of R-290/600a in mobile air-conditioning (MAC) systems

G. Rolotti (Elf Atochem North America, Incorporated), **Issues and Findings Over 2 Years of MAC Retrofits**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 526-535, October 1995 (10 pages with 1 figure and 2 tables, available from JMC as RDB5B22)

R-12 to R-134a retrofit of mobile air-conditioning (MAC) system, refrigerant losses, failures, user perceptions, flushed versus non-flushed results

Marine Refrigeration and Air Conditioning Systems

R. L. Mansmann (Ashland Chemical Company), **Retrofitting Marine Refrigeration and Air Conditioning Systems to HFC Refrigerants**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 179-186, October 1995 (8 pages with no figures or tables, RDB5A57)

R-12, R-22, R-134a, lubricants

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Valves and Accessories

S. Adachi (Union Showa K.K., Japan), **Development of Molecular Sieve Desiccants for Alternative Refrigerants**, paper 5.6, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 130-134, December 1994 (5 pages with 11 figures and 3 tables; in Japanese with abstract, figures, and tables in English; RDB5424)

R-32; 4A XH-5, 4A NRG, 4A XH-6, XH-9, XH-10c, and developmental molecular sieves; compatibility tests

A. H. Blom (Danfoss A/S, Denmark), **Filter Driers for Alternative and Transitional Refrigerants**, *Ki Luft- und Kältetechnik*, Germany, 31(10):468-471, 1995 (4 pages in German, rdb6309)

R-134a, requirements and sizing for filter driers to absorb water and acid in refrigeration systems, filtration efficiency, compatibility with hydrofluorocarbon (HFC) refrigerants, polyolester (POE) lubricants and additives

A. P. Cohen and C. S. Blackwell (UOP), **Inorganic Fluoride Uptake as a Measure of Relative Compatibility of Molecular Sieve Desiccants with Fluorocarbon Refrigerants**, paper 3909, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):341-347, 1995 (7 pages with 4 figures and 5 tables, RDB6335)

R-32, molecular sieve desiccants, reaction of refrigerant with desiccant

A. P. Cohen and S. R. Dunne (UOP), **Review of Automotive Air Conditioners Drydown Rate Studies - The Kinetics of Drying Refrigerant 12**, *Transactions* (Annual Meeting, Nashville, TN, 27 June - 1 July 1987), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 93(2):725-735, 1987 (11 pages with 7 figures and 4 tables, RDB5552)

R-12, 4Å molecular sieve, silica gel

O. S. Hernandez (Uberlândia Federal University, Brazil) and S. A. Lopes (Ouro Preto Federal University, Brazil), **Performance of a Medium Size, Constant Superheating PC-Controlled Expansion Valve for Chillers**, *Proceedings of the 1994 International Refrigeration Conference at Purdue,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 359-364, July 1994 (6 pages with 7 figures, RDB4846)

R. H. Kim (University of North Carolina), **A Numerical Analysis of a Capillary Tube Expansion Valve in a Vapor-Compression Refrigeration System with Alternative Refrigerants,** *Heat Transfer with Alternate Refrigerants* (proceedings of the 29th National Heat Transfer Conference, Atlanta, GA, 8-11 August 1993), edited by H. J. Sauer, Jr., and T. H. Kuehn, American Society of Mechanical Engineers (ASME), New York, NY, HTD-243:43-51, 1993 (9 pages with 10 figures and 5 tables, rdb3B19)

Other

C. Arzano (Électricité de France, ÉDF, France), D. Clodic (École des Mines de Paris, France), B. Hivet and C. Ducruet (ÉDF), **Influence of Thermodynamic Parameters in a Vapour Compression Cycle**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 247-252, July 1996 (6 pages with 9 figures and 2 tables, RDB6910)

R-12, R-22, R-134a, R-142b, R-152a, R-290, R-C318 (identified in the paper as FC 318), R-600a, and R-717: influence of molar heat capacity on performance; mathematical models for compression, desuperheating, expansion, subcooling, heat transfer, cycle calculations; role of liquid-vapor heat exchanger and determination of when it is advantageous

T. Broccard (Hussmann Corporation), **A Revolutionary New Approach to Supermarket Refrigeration**, *Proceedings of the 45th Annual International Appliance Technical Conference* (University of Wisconsin, Madison, WI, 9-11 May 1994), IATC, Batavia, IL, 61-69, May 1994; republished in *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 313-321, October 1995 (9 pages with 7 figures, RDB4A26)

This paper presents an approach for reducing the amount of refrigerant used in supermarket systems. It employs decentralized, water-cooled, condensing units located in close proximity to the display cases served. The concept differs from traditional practice, based on centralized equipment rooms. The new system introduces three ways to reduce the required refrigerant charge. First, the reduced line lengths lower the inventory, especially in the liquid line. Second, the internal volume is lowered by using smaller tubing sizes, since large diameters are no longer needed to minimize pressure drops for long runs. Third, use of compact, water-cooled, brazed plate, heat exchangers enables heat rejection to an intermediate water circuit, piped to fluid coolers on the roof or rear of the store. Doing so avoids the need for flooded condensers, to maintain head pressure at low ambient temperatures. The paper outlines and illustrates the concept. It indicates that refrigerant charge was reduced by 50% and joints by 50-75% in demonstration applications. The paper then reviews customer concerns that had to be resolved to make the system viable. They include control of in-store noise and serviceability, avoidance of lost merchandising space, loss of heat reclaim, and potential increases in electrical distribution costs. The paper outlines a solution, predicated on use very compact, multiplexed scroll compressors serving closely-located display cases with similar suction temperatures. The paper also indicates that R-404A, described as "an environmentally-friendly refrigerant," was selected. Heat reclaim is addressed by drawing heat from the heat rejection fluid or from a heat-reclaim condenser coil. The paper concludes that the microprocessor controlled system offers reduced refrigerant charge, reduced opportunities for leaks, lower installed costs, and reliable and simplified systems.

J. Calhoun (Sanden International, Incorporated), **The Impact of HFC-134a on the Manufacture and Service of Automotive Air Conditioning Compressors**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC), Alliance for Responsible CFC Policy, Arlington, VA, 285-293, October 1993 (9 pages with 8 figures, RDB3A49)

S. Corr, F. T. Murphy (ICI Chemicals and Polymers, Limited, UK), and S. Wilkinson (ICI Engineering, UK), **Composition Shifts of Zeotropic HFC Refrigerants in Service**, paper OR-94-1-2, *Transactions* (Annual Meeting, Orlando, FL, 25-29 June 1994), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 100(2):538-546, 1994 (9 pages with 8 figures, RDB4702)

R-32, R-125, R-134a, R-143a, R-32/125 (60/40), R-32/125/134a (24/16/60) and (30/10/60)

M. A. Di Flora (Bristol Compressors, Incorporated), **Alternative Refrigerant Effect on Compressor Design,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 194-199, October 1995 (6 pages with 5 presentation charts, available from JMC as RDB5A59)

R-22 replacements

P. A. Domanski, D. A. Didion (National Institute of Standards and Technology, NIST), and J. P. Doyle (Giant Foods, Incorporated), **Evaluation of Suction Line - Liquid Line Heat Exchange in the Refrigeration Cycle,** *Proceedings of the 1992 International Refrigeration Conference - Energy Efficiency and New Refrigerants*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 1:131-139, July 1992; republished in the *International Journal of Refrigeration* (IJR), 17(7):487-493, September 1994 (9/7 pages with 7 figures and 1 table, RDB54A6)

R-11, R-12, R-13, R-13B1, R-14, R-22, R-23, R-32, R-113, R-114, R-115, R-123, R-124, R-125, R-134, R-E134, R-134a, R-141b, R-142b, R-143a, R-152a, R-170, R-216a (sic), R-216b (sic), R-218, R-290, R-C270, R-C318, R-600a

P. A. Domanski and D. A. Didion (National Bureau of Standards, NBS), **Equation-of-State-Based Thermodynamic Charts for Nonazeotropic Refrigerant Mixtures**, paper CH-85-05-2, *Transactions* (Winter Meeting, Chicago, IL, 27-30 January 1985), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 91(1), January 1985 (9 pages with 6 figures, RDB6426)

R-13B1/152a, composition management for capacity control

E. D. Fry (Tecumseh Products Company), **Compressor Technology Trends**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 200-205, October 1995 (6 pages, available from JMC as RDB5A60)

effects of new refrigerants and lubricants on compressors

R. W. Griffith (Copeland Corporation), **Alternate Refrigerants for the Refrigeration Industry**, *R-22 and R-502 Alternatives* (Proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 19-20 August 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 19-21, 1994 (3 pages with 4 figures, RDB4516)

This paper reviews the refrigerant aspects, and corresponding implications, that a compressor manufacturer must examine when evaluating a refrigerant for suitability. They include the effects on performance, compression temperature, discharge pressure and compression ratio, and motor design including materials compatibility. A figure compares the saturation pressures of R-402A (DuPont Suva® HP80), R-402B (Suva HP81), R-404A (Suva HP62 or Atochem Forane® FX-70), and R-507A (AlliedSignal Gen-

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etron® AZ-50) to that of R-502 for a discharge temperature of 54 °C (130 °C). It similarly compares R-407C (Suva 9000), R-410A (Genetron AZ-20), and two unspecified blends of R-32/134a to R-22. It also compares R-134a, R-401A (Genetron and Suva MP39), and R-401B (Genetron and Suva MP66) to R-12. The paper then discusses issues associated with zeotropic blends including their temperature glides, fractionation, and charging. Turning to performance, the paper notes that the heat transfer characteristics of the new refrigerants are better than the original fluids, leading to comparable or improved capacity and efficiency. The paper then addresses lubricants, with emphasis on polyolesters (POEs). A figure compares the hygroscopicity of an unidentified POE and mineral oil. The author observes that POE may break down to its original acid and alcohol constituents in the presence of excessive moisture, leading to copper plating and rusting. The higher solvency of POE than mineral oil, however, may lead to a cleaner system. A second figure and related discussion indicate that an R-404A/POE mixture may yield a higher maximum cylinder pressure under flooded start conditions. A final figure compares the sound levels of three compressors using R-22 with a POE and a mineral oil. The paper notes that POEs are more quiescent, and that lower foaming with POEs may result in somewhat noisier operation. The author concludes that many new refrigerants are being introduced and that while similar to those they replace, they are not identical. The new refrigerants appear promising from many standpoints, but they will require changes in handling and charging procedures.

H. M. Hughes, W. P. Dulaney, and R. L. Broussard (AlliedSignal Incorporated), **A Refrigerant Producer's Experience in Manufacturing Zeotropic Blends**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 101-106, July 1996 (6 pages with 1 table, RDB6818)

R-407C, blending and packaging of refrigerant blends; fractionation; composition tolerances; product specifications: addresses the influences of blending equipment, techniques, quantity of components, blend formulation, temperature, and any residual "heel" (remainder of out-of-tolerance blend from preceding tank draw-down) on maintenance of zeotropes within product specifications during container filling operations

P. Linnert (The Trane Company), **Rotary Compressor Technology - Meeting the Needs of the Future**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 187-193, October 1995 (7 pages with 4 figures, available from JMC as RDB5A58)

compressor trends, refrigerant selection, R-134a, R-407C, R-410A, efficiency

J. D. Morrison, S. Corr (ICI Chemical and Polymers, UK), and B. E. Gilbert (ICI Klea, UK), **Production-Scale Handling of Zeotropic Blends,** paper PH-97-9-2, *Transactions* (Winter Meeting, Philadelphia, PA, 26-29 January 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 103(1):756-764, 1997 (9 pages with 7 figures and 1 table, RDB7C15)

examination of composition shifts for R-407 series (R-32/125/134a) zeotropic blends during bulk handling and individual-system charging for conditions representative of an equipment factory supplied by bulk deliveries; effects of repeated recharges of the bulk tank; thermodynamic model for vapor-liquid equilibria (VLE) compositions and effects of vapor leakage, temperature, charging to intermediate vessels, and composition specifications; resulting model can be used to develop a plan for composition management by adjusted (compensating) recharges

K. Nakatani, M. Matsuo, Y. Yoshida, and Y. Kuwari (Matsushita Electric Industrial Company, Limited, Japan), **Development of Simulation for Refrigerator Using HFC134a,** *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:925-932, 1995 (8 pages with 5 figures and 2 tables, rdb7931)

simulation program to determine the performance of refrigeration cycles, consisting of a compressor, condenser, capillary tube, and evaporator and the temperature of each compartment in domestic refrigerators using R-134a; validation with measured data

R. C. Niess, **CFCs and Electric Chillers - Selection of Large-Capacity Water Chillers in the 1990s**, report TR-100537, Electric Power Research Institute (EPRI), Palo Alto, CA, March 1992 (188 pages with 3 figures and 34 tables, RDB2A18)

J. R. Parsnow (Carrier Corporation), **Three Important Questions to Answer on Alternative Refrigerants,** *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 40-45, November 1997 (6 pages with 1 figure and 2 tables, RDB8325)

suggests three questions to ask as a guide in choosing among alternative refrigerants: (1) Has the refrigerant been approved under the U.S. Environmental Protection Agency (EPA) Significant New Alternatives Program (SNAP)? (2) Has the refrigerant been recognized by industry standards? And (3), has the original equipment manufacturer (OEM) approved the refrigerant in the intended application? Paper discusses these issues, information sources, and tabulates information on selected refrigerants.

J. Peters (Bundesfachschule Kälte-Klima-Technik, Germany), **Designing and Building a Hydrocarbon-Based Commercial Refrigeration System to Customer Specifications**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 303-310, October 1995 (8 pages with 3 figures and 2 tables, available from JMC as RDB5B05)

R-290, comparisons to R-22, use, performance, safety

P. Pieczarca and J. Lavelle (Elf Atochem North America, Incorporated), **Storage, Bulk Transfer, and In-Plant Handling of Zeotropic Refrigerant Blends**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 107-112, July 1996 (6 pages with 4 figures and 1 table, RDB6819)

R-407C, delivery truck and bulk tank operations for a refrigerant blend with a high temperature glide, adjustments to maintain blend composition, progressive change in composition

J. H. Robinson (Young Life) and D. L. O'Neal (Texas A&M University), **The Impact of Charge on the Cooling Performance of an Air-to-Air Heat Pump for R-22 and Three Binary Blends of R-32 and R-134a**, paper OR-94-1-1, *Transactions* (Annual Meeting, Orlando, FL, 25-29 June 1994), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 100(2):529-537, 1994 (9 pages with 8 figures and 9 tables, RDB4701)

R-32/134a (40/60), (30/70), and (22/78)

E. R. Rodgers (Arlington County), **Obtaining Approval for the Use of Non-CFC Refrigerants in Your Building**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 20-22 October 1993), Alliance for Responsible Atmospheric Policy, Arlington, VA, 246-249, October 1993 (4 pages, RDB6321)

building code, mechanical code, alternate methods and materials, waiver

S. M. Sami and M. A. Comeau (University of Moncton, Canada), **Experimental Study of the Dynamic Behavior of Non-Azeotropic Binary Mixtures in Heat Pumps**, *Heat Recovery Systems and CHP,* 11(6):505-515, 1991 (11 pages with 15 figures and 1 table, RDB6715)

R-22/114 (80/20), (60/40), (40/60), and (20/80); R-22/152a (90/10), (80/20), and (70/30); undisclosed binary zeotrope identified as *NARM/UM*: experimental study of dynamic behavior in an 11 kW (3 ton) water-to-air heat pump during the heating mode under start-up conditions; found a 35% improvement in efficiency over R-22 for *NARM/UM*; plots show the pressures and temperatures of the blends at key locations in the refrigerant circuit during transient start-up conditions; concludes that the state of the refrigerant and its composition have a significant effect on performance and that zeotropic mixtures offer potential as refrigerants in heat pump applications

E. L. Smithart (The Trane Company), **Choosing a Building Chiller**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 20-22 October 1993), Alliance for Responsible Atmospheric Policy, Arlington, VA, 250-258, October 1993 (9 pages, with 13 figures and 9 tables, RDB6322)

R-123, centrifugal chillers, availability, cost, safety, emissions, environmental considerations, transition planning

A. Stegou-Sagia and D. Katsanos, **On Isentropic Changes of Alternative Refrigerants (R-123, R-134a, R-500, R-503)**, *Energy,* 21(12):1071-1077, 1996 (7 pages, rdb8367)

refrigerant properties

R. L. Webb, A. S. Wanniarachchi, and T. M. Rudy (Pennsylvania State University), **The Effect of Noncondensible Gases on the Performance of an R11 Centrifugal Water Chiller Condenser**, *Transactions* (Annual Meeting, Denver, CO, 22-26 June' 1980), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 86(2):19-27, 1980 (9 pages with 6 figures and 2 tables, RDB5263)

R-11, performance, purge requirements

F. J. Wiesner, Jr., and H. E. Caswell, **Effects of Refrigerant Properties on Centrifugal Compres-**

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sor Impeller Dimensions and Stage Performance, *Transactions,* American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 65, 355-376, 1965 (22 pages, RDB4128)

E. F. Wojtkowski**, System Contamination and Cleanup**, *ASHRAE Journal,* 49-52, June 1964 (4 pages, RDB4747)

R. Yajima, N. Domyo, S. Taira, and I. Tarutani (Daikin Industries Limited, Japan), **Selections and Applications of New Refrigerants for Air Conditioners**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 82-91, November 1997 (10 pages with 10 figures and 2 tables, RDB8330)

evaluation of R-407C and R-410A as replacements for R-22 in split-system, room air conditioners and heat pumps

CFCs and Electric Chillers - Selecting Large Water Chillers as CFCs Are Phased Out, brochure CU.2039R.7.92, Electric Power Research Institute (EPRI), Palo Alto, CA, July 1992 (6 pages with 4 figures, RDB3454)

CFCs and Electric Utilities - Making the Transition to a Safer World, report CU-7027 (project RP2792-12), Electric Power Research Institute (EPRI), Palo Alto, CA, October 1990 (76 pages with 29 figures, RDB3455)

This report provides an illustrated narrative, based on a series of slide presentations, to review the phase out of chlorofluorocarbon (CFC) refrigerants, their use in electric-powered equipment, and estimates of phaseout impacts. The tie between the chemical composition of refrigerants and stability, flammability, and toxicity is illustrated. Data on the ozone-depletion potential (ODP), global warming potential (GWP) and atmospheric lifetime also are indicated. The report reviews data on use of refrigerants by application and resultant electric utility loads and revenues. The report notes that utility income from these sources is more than double that received by other industry participants. Likely alternative refrigerants as well as their impacts on equipment cost, efficiency, resultant energy consumption, and loads are projected.

Control of Frost Accumulation in Refrigeration Equipment using the Electrohydrodynamic (EHD) Technique, proposed research project 1100-TRP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1999 - March 2001 (ASH 1100)

This research project will investigate use of the electrohydrodynamic (EHD) technique to control frost growth on evaporators. Experiments will measure frost control (namely, reduced frost mass accumulation) and power consumption for a selected heat transfer surface and electrode geometry under representative operating conditions for refrigeration applications. The findings will be assembled into a database on the influences of controlling parameters including steady and pulsed operation, air temperature, heat transfer surface temperature, air humidity, and flow Reynolds number. This research project is sponsored by ASHRAE Technical Committees 8.4, *Air-To-Refrigerant Heat Exchangers*, and 1.3, *Heat Transfer and Fluid Flow*. Proposals are due at ASHRAE Headquarters by 18 December 1998. Further information is available from the ASHRAE Manager of Research (+1-404/636-8400).

DuPont HCFC-123: Properties, Uses, Storage and Handling, bulletin P-123 (H-52157), DuPont Chemicals, Wilmington, DE, November 1993 (24 pages with 7 figures and 10 tables, RDB7212)

This document provides extensive application information for R-123. It reviews identifiers and potential uses, shows an infrared spectrum for laboratory analyses, compares theoretical and retrofit performance to R-11, discusses its use as a heat transfer fluid, and summarizes physical properties as well as flammability, environmental, and toxicity indices. Plots of solubility in water and pressure-temperature relationships are included. Pressure-enthalpy diagrams, in both inch-pound (IP) and metric (SI) units, are provided. The bulletin reviews chemical and thermal stability data, including thermal decomposition and stability with metals and refrigeration lubricants. It then addresses compatibility with plastics, elastomers, desiccants, and refrigeration lubricants. A table presents compatibility ratings with plastics following exposures for 4 hours 24 °C (75 °F) and for 100 hours at 54 °C (130 °F). the plastics include ABS polymer (Kralastic®), acetal (DuPont Delrin®), acrylic (Lucite®), polytetrafluoroethylene (PTFE, DuPont Teflon®), nylon 6/6 polyamide (DuPont Zytel®), polycarbonate (GE Lexan®), polyethylene-HD (Alathon®), polypropylene (Alathon®), polystyrene (Styron®), and polyvinyl chloride (PVC or CPVC). Length (swell) and weight change data, based on 7 day exposures at 54 °C (130 °F) also are tabulated for R-123 compatibility with a butyl rubber, chlorosulfonated polyethylene (CSM, DuPont Hypalon®), fluoroelastomer (DuPont Viton® A), hydrocarbon rubber (DuPont Nordel®), natural rubber, neoprene, nitrile rubber (NBR, Buna N, and SBR, Buna S), polysulfide rubber (Thiokol® FA), silicone rubber, and urethane rubber (Uniroyal Adprene® C). Solubility data are provided for R-123 in unidentified naphthenic and paraffinic mineral oils and alkylbenzene lubricants. Safety data are then presented, including a review of inhalation toxicity, cardiac sensitization, responses to spills or leaks, and skin and eye contact. The report recommends an Acceptable Exposure Limit (AEL) of 30 ppm for 8 and 12 hours on a time-weighted average (TWA) basis. Monitors and leak detection are discussed as are storage, handling, and shipping. The bulletin concludes with discussion of recovery, reclamation, recycling, and disposal.

DuPont HFC-134a: Properties, Uses, Storage and Handling, bulletin P134a (H-45945-3, 233264D), DuPont Chemicals, Wilmington, DE, September 1997 (28 pages with 10 figures and 20 tables, RDB7C06)

This document provides extensive application information for R-134a. It reviews identifiers and potential uses, shows an infrared spectrum for laboratory analyses, compares theoretical performance to R-12, and summarizes physical properties as well as flammability, environmental, and toxicity indices. Plots of solubility in water, pressure-temperature relationships, and vapor thermal conductivity are included. Pressure-enthalpy (PH) diagrams, in both inch-pound (IP) and metric (SI) units, are provided. The bulletin reviews chemical and thermal stability data, including thermal decomposition, stability with metals and refrigeration lubricants, stability with foam chemicals, and concerns if mixed with R-12. It then addresses compatibility with plastics, elastomers, desiccants, and refrigeration lubricants. A table indicates "meriting further testing" or "unacceptable change" with plastics including ABS polymer (Kralastic®), acetal (DuPont Delrin®), acrylic (Lucite®), cellulosic (Ethocel®), epoxy, polytetrafluoroethylene (PTFE, DuPont Teflon®), ETFE (Tefzel®), PVDF, ionomer (Surlyn®), nylon 6/6 polyamide (DuPont Zytel®), polyarylate (Arylon®), polycarbonate (Tuffak®), polybutylene terephthalate (PBT, GE Valox®), polyethylene terephthalate (PET, DuPont Rynite®), polyetherimide (GE Ultem®), polyethylene-HD (Alathon®), polyphenylene oxide (PPE, GE Noryl®), polyphenylene sulfide (Ryton®), polypropylene, polystyrene (Styron®), polysulfone (Polysufone®), and polyvinyl chloride (PVC and CPVC). A tabular summary indicates R-134a compatibility ratings with a urethane rubber (Uniroyal Adiprene® L), Buna N, Buna S, butyl rubber, synthetic rubber (DuPont Hypalon® 48), natural rubber, neoprene W, hydrocarbon rubber (DuPont Nordel®), silicone rubber, polysulfide rubber (Thiokol® FA), and fluoroelastomer (DuPont Viton® A). Further tables summarize changes in length, weight, Shore A hardness, elasticity, and appearance after exposures at 25, 80, and - for some elastomers - 141 °C (77, 176, and 285 °F). A table summarizes permeation through elastomeric hoses made of nylon, Hypalon 48, and two nitriles with identified liners, reinforcement, and covers. Solubility data are provided for R-134a in unidentified naphthenic and paraffinic mineral oils, dialkylbenzene, alkylbenzene, polyalkylene glycol (PAG), and ester lubricants. Safety data are then presented including a review of inhalation toxicity, cardiac sensitization, responses to spills or leaks, and skin and eye contact. Flammability data, exposure monitors, and leak detection are discussed as are storage, handling, and shipping. The bulletin concludes with discussion of recovery, reclamation, recycling, and disposal.

DuPont Suva® HP Refrigerant Blends: Properties, Uses, Storage, and Handling, bulletin P-HP (H-47122-2), DuPont Chemicals, Wilmington, DE, February 1994 (28 pages with 9 figures and 7 tables, available from JMC as RDB4503)

This document provides extensive application information for R-402A and R-402B, both blends of R-125, R-290, and R-22 - R-125/290/22 (60/2/38) and R-125/290/22 (38/2/60) respectively. It also addresses R-404A, a blend of R-125, R-143a, and R-134a - R-125/143a/134a (44/52/4). It reviews identifiers, the blend compositions, and potential uses. The bulletin then summarizes physical properties as well as flammability, environmental, and toxicity indices. Pressure-enthalpy diagrams are provided in both metric (SI) and inch-pound (IP) units. The bulletin reviews chemical and thermal stability data, including thermal decomposition. A table provides representative data on stability with metals (copper, iron, and aluminum) based on sealed-tube tests of mixtures of R-402B with mineral oil (Witco Suniso® 3GS), alkylbenzene (Shrieve Zerol® 150 TD), and a branched acids polyolester (Castrol Icematic® SW32) lubricants. Results also are provided for R-404A with the same lubricants and a mixed acids ester (Mobil EAL Arctic® 22). The report reviews compatibility of the refrigerant blends with R-502, noting chemical compatibility, but potential performance differences and separation difficulty, the latter leading to a need for disposal by incineration. It then addresses compatibility with elastomers; a tabular summary is provided for five polymers with combinations of the cited lubricants and R-502, R-402B, and R-404A. The compounds tested were polytetrafluoroethylene (PTFE, DuPont Teflon®) in commercial grade sheet from Tex-O-Lon Manufacturing), Buna N nitrile butadiene (NBR, Parker Seal), hydrogenated NBR (HNBR, Parker Seal N11951,

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chloroprene (CR, Precision Rubber neoprene W), and EPDM (Kirkhill Rubber). Compatibility data also are discussed for polyethylene terephthalate (PET, DuPont Mylar® film), polyesterimide motor wire with amide-imide overcoating, and Dacron/Mylar/Dacron® lead wire (Belden) as well as for molecular sieve desiccants (UOP 4A-XH-5 and XH-9). Miscibility is summarized for R-502 and the three zeotropes with mineral oil, alkylbenzene, and polyolester lubricants. Safety data are then presented including a review of inhalation toxicity, cardiac sensitization, responses to spills or leaks, skin and eye contact, and flammability. Monitors and leak detection are discussed as are storage, handling, and shipping. The bulletin concludes with discussion of recovery, reclamation, recycling, and disposal. DuPont's product names for R-402A, R-402B, and R-404A are Suva® HP80, Suva® HP81, and Suva® HP62 respectively.

DuPont Suva® MP Refrigerant Blends: Properties, Uses, Storage, and Handling, bulletin P-MP (H-45944), DuPont Chemicals, Wilmington, DE, December 1992 (36 pages with 14 figures and 13 tables, available from JMC as RDB3441)

This document provides extensive application information for R-401A, R-401B, and R-401C - R-22/152a/124 (53/13/34), (61/11/28), and (33/-15/52), respectively. It reviews identifiers, the blend compositions, potential uses, compares theoretical performance to R-12, and discusses temperature glides. Using R-401A as an illustration, it presents tabular data on the theoretical effect of leakage on performance. The bulletin then summarizes physical properties as well as flammability, environmental, and toxicity indices. Plots of pressure-temperature relationships and pressure-enthalpy diagrams, in both inch-pound (IP) and metric (SI) units, are provided. The bulletin reviews chemical and thermal stability data, including thermal decomposition. A table provides representative data on stability with metals (copper, iron, and aluminum) and refrigeration lubricants; comparative information is given for R-12 with two mineral oils. The lubricants addressed include alkylbenzenes (Shrieve Zerol® 150DL, 300, and 500T), branched acids polyolesters (Castrol Icematic® SW22, SW32, SW68, and SW100), mixed acids polyolesters (Mobil EAL Arctic® 68, Henkel Emery® ISO 10 and 100, and Lubrizol ISO 150). It then addresses compatibility with elastomers; a tabular summary is provided for R-22/152a/124 (36/24/40), Zerol® 500, and a 50/50 mixture with 11 polymers including natural rubber (NR), butyl rubber (IIR), EPDM (DuPont Nordel®), chloroprene (CR, DuPont Neoprene® W), styrene-butadiene copolymer (SBR, Buna-S), Buna N nitrile (NBR, Polysar Krynac®), hydrogenated NBR (HNBR, Polysar Tornac®), chlorosulfonated polyethylene (CSM, DuPont Hypalon® 48), fluoroelastomer (FKM, DuPont Viton®), silicone rubber (SI, Dow Silastic®), epichlorohydrin homopolymer (CO, Goodrich Hydrin® 100), epichlorohydrin copolymer (ECO, Goodrich Hydrin® 200), urethane (Uniroyal Adiprene®), and polysulfide rubber (T, Thiokol® FA). A separate table summarizes the compatibility of R-401C, a mixture of this refrigerant with Zerol® 500T and a mineral oil (BVM 100N), and Zerol® 500T alone with 5 polymers; they include CR (DuPont Neoprene®), NBR nitrite, HNBR, CO, and ECO. Compatibility data also are provided for polyester insulation material for motors and for molecular sieve desiccants (UOP 4A-XH-5 and XH-9). Miscibility data are provided for 30, 60, and 90% weight lubricant mixtures with R-401B and naphthenic mineral oil, paraffinic mineral oil, alkylbenzenes, polyolesters, and the latter two also with mineral oils. Hose permeation rates are presented for nylon-lined and nitrile hoses. Safety data are then presented including a review of inhalation toxicity, cardiac sensitization, responses to spills or leaks, skin and eye contact, and flammability. Monitors and leak detection are discussed as are storage, handling, and shipping. The bulletin concludes with discussion of recovery, reclamation, recycling, and disposal. DuPont's product names for R-401A, R-401B, and R-401C are Suva® MP39, Suva® MP66, and Suva® MP52, respectively.

Forane® for Refrigeration and Air Conditioning, bulletin DIREP-1985E, Elf Atochem S.A., Paris - La Defense, France, January 1994 with addendum dated May 1994 (23 pages with 13 tables, RDB-4B16)

This bulletin outlines the replacement offerings of Elf Atochem for chlorofluorocarbon (CFC) refrigerants. It reviews the schedule for CFC phaseout and provides a table showing the applications of R-11, R-12, R-22, R-123, R-134a, R-142b, R-404A, R-409A, R-500, and R-502 as well as R-22/124/142b (65/25/10), R-23/32/134a (4.5/21.5/74), R-32/125/143a (10/45/45), and R-143a/22 (55/45). It briefly discusses lubricants, including the Elf Atochem polyolesters (Planetelf®), and filter driers, including CECA's - an Elf Atochem subsidiary - molecular sieves (Siliporite®) for alternative refrigerants. The bulletin comments on leak detection methods and then discusses conversion of existing systems, with specific attention to R-123 for R-11; R-134a, R-409A, and R-22/124/142b (65/25/10) for R-12; R-404A, R-32/125/143a (10/45/45), and R-143a/22 (55/45) for R-502; and R-23/32/134a (4.5/21.5/74) for R-22. Tabular swell data are provided for the cited refrigerants with plastics and elastomers, including polychloroprene (Neoprene), butadiene acrylonitrile (BNR, Buna N), butadiene styrene (Buna S), hexafluoropropylene/vinylidene fluoride (Viton) butyl rubber (IIR), chlorosulfonated polyethylene (Hypalon), polyamide 11 (Rilsan), polystyrene (PS), and polyvinyl chloride (PVC). Summary property data (chemical formula, chemical name, molecular mass, bubble temperature, temperature drop (glide), critical temperature, critical pressure, pressure and density at representative conditions, ozone depletion potential (ODP), global warming potential (GWP), and flammability limits) and safety data (toxicity, recommended exposure limits, and flammability limits) also are tabulated. The bulletin concludes with brief discussion of handling, storage, recovery, recycling, and the company's quality program. Elf Atochem's product names for R-404A and R-409A are Forane® FX-70 and FX-56, respectively. Its names for R-22/124/142b (65/25/10), R-23/32/134a (4.5/21.5/74), and R-32/125/143a (10/45/45) are Forane® FX-57, FX-220, and FX-40, respectively. Its name for R-143a/22 (55/45) until 9 May 1994 was FX-10, when it was reformulated as R-125/143a/22 (7/46/47) – R-408A. An addendum explains revision of the formulation to meet the Underwriters Laboratories (UL) requirements for classification as "practically nonflammable," as requested by equipment manufacturers in the United States. The addendum provides two tables with comparative data for the physical characteristics and performance of the initial and revised formulations of FX-10. The conclusions state that the two blends can be mixed, characteristics remain unchanged, and the materials compatibility and retrofit guidelines are the same.

Isceon 69-L, product bulletin, National Refrigerants, Incorporated, Philadelphia, PA, undated circa 1993 (4 pages containing 4 figures and 2 tables, RDB3A65)

This bulletin provides application information for R-403B, a ternary zeotropic blend of R-22, R-218, and R-290 formulated as R-290/22/218 (5/56/39). The bulletin outlines the development and applications of the blend, and discusses its use as a service fluid for retrofit of R-502 systems. A plot compares the ozone depletion potential (ODP) of the blend with those of R-12, R-22, R-115, and R-502, showing the blend to be the lowest. Two plots and a table compare the capacities and efficiencies of R-502 and the blend for evaporator temperatures of -37 to -21 °C (-35 to -5 °F) and condensing temperatures of 41 and 49 °C (105 and 120 °F); they show higher theoretical capacity and efficiency for the blend. A figure shows how the composition varies as vapor is drawn from a cylinder, leading to the conclusion that charging should be from the vapor phase unless the entire cylinder is to be used in a large system. The document also discusses fractionation under leakage, noting that the propane (R-290) content will not rise above that of the original formulation. Potential liquid and vapor leaks are described as nonflammable, both for the escaping fluid and that remaining in the system. A final table provides physical properties, in inch-pound units. Rhône-Poulenc Chemical's product name for R-403B is Isceon 69-L; National Refrigerants is the exclusive distributor for North America.

Refrigerant Piping Installation/Servicing Manual for Air Conditioners Using R410A, Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, December 1997 (34 pages with 8 figures and 15 tables in English; RDB9831)

provides guidance on installation and service of equipment using R-410A: compares physical and environmental data for R-22 and R-410; discusses safety issues for R-410A; presents recommended practices for piping and equipment installation, servicing, and removal; outlines refrigerant recovery procedures

SAFETY

Editor's Note:

The citations on SAFETY/Toxicity (pages 235-383) appear in full in their most up-to-date version (at the time of publication) in Appendix 4 of DOE/CE/23810-110, *Toxicity Data to Determine Refrigerant Concentration Limits* by J. M. Calm (September 2000).

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Lubricants

T. L. Chan, M. J. Olson, J. A. Baker, D. L. Farley, and H. F. Hutchins (General Motors Research Laboratories), **Exposure Assessment and Hazard Evaluation of a Polyoxyalkylene Glycol Aerosol Released from a Non-CFC Mobile Air-Conditioning System**, *AIHA Journal,* 56(9):898-904, September 1995 (7 pages with 13 figures, rdb7C79)

toxicity of polyoxyalkylene glycol (PAG) lubricants: outlines four scenarios chosen to simulate worst-case exposures of drivers, mechanics, or test engineers to a release of an aerosol containing the PAG; reports the time-averaged total airborne particulate concentration over a 20-minute period as 0.1-42 mg/m^3; concludes that an adverse pulmonary response in humans is unlikely given the remote likelihood of the four release scenarios and the relatively low toxicity of a PAG aerosol; also notes that an unexpected exposure of mechanics servicing mobile air conditioning (MAC) systems to <0.1 mg/m^3 represents a minimal health risk

D. A. Kalman, K. J. Voorhees, D. Osborne, and I. N. Einhorn, **Production of Bicyclophosphate Neurotoxic Agent During Pyrolysis of Synthetic Lubricant Oil**, *Journal of Fire Sciences,* 3:322 ff, 1985 (rdb6381)

lubricants, safety, toxicity

G. D. Nielsen (Danish National Institute of Occupational Health, Denmark) and Y. Alarie (University of Pittsburgh), **Sensory Irritation, Pulmonary Irritation, and Respiratory Stimulation by Airborne Benzene and Alkylbenzenes: Prediction of Safe Industrial Exposure Levels and Correlation with Their Thermodynamic Properties**, *Toxicology and Applied Pharmacology* (TAP), 65:459-477, 1982 (19 pages with 10 figures and 4 tables, rdb6505)

lubricants, safety, toxicity, sensory irritation, RD_{50}

J. D. Smith et al., **Health Aspects of Lubricants**, report 5/87, CONCAWE, The Hague, The Netherlands, 1987 (rdb6383)

safety, toxicity

Flammability

F. J. Benz, C. V. Bishop, and M. D. Pedley, **Ignition and Thermal Hazards of Selected Aerospace Fluids**, report RD-WSTF-0001, Lyndon B. Johnson Space Center, National Aeronautics and Space Administration, White Sands Test Facility, New Mexico, 1988 (RDB4B61)

R-717 (ammonia), flammability

W. L. Bunkley and H. W. Husa, **Combustion Properties of Ammonia**, *Chemical Engineering Progress*, 58(2):81-84, 1962 (4 pages, RDB4863)

R-717 (ammonia), LFL, UFL

L. W. Burgett (The Trane Company), **Flammable Refrigerants: Equipment Manufacturer Concerns**, presentation 3.3, *ARI Flammability Workshop - Summary and Proceedings* (Chicago, 8-9

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March 1994), Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1994 (22 pages with 19 presentation charts, available from JMC as RDB-4792)

R. C. Cavestri and E. Falconi (Imagination Resources, Incorporated, IRI), **An Objective Method for Determining Refrigerant Flammability**, presentation 2.3, *ARI Flammability Workshop - Summary and Proceedings* (Chicago, 8-9 March 1994), Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1994 (10 pages with 29 presentation charts, available from JMC as RDB4786)

These presentation charts outline a study of the use of imaging spectroscopy and reduced-pressure combustion methods to evaluate refrigerant flammability. These techniques are suggested to be more objective than the standard ASTM E681 method, which depends on visual identification of flame propagation. The introductory chart notes that observers perceive flame quality and colors differently. It also describes characteristics of true flame initiation, which begins with ultraviolet (UV) emission and is always associated with a visible continuum with known emission energy and wavelengths. Two charts show a schematic of the combustion chamber used for tests and the spectral spark response of dry nitrogen, as a reference for a nonflammable gas. A series of spectral plots show the responses R-143a in dry nitrogen, helium, and air for varied concentrations and for a series of repeated spark initiations. Some of the plots illustrate the spectral response at reduced cell pressures, to show transient pressure and temperature rises. The sensitivity of the temperature and pressure rises to the degree of pressure reduction are plotted. Spectra of spark responses also are shown for R-134a in dry helium and ambient air and for R-125 in ambient air. A concluding chart indicates that imaging spectroscopy is an effective analytical tool for differentiating between chemical ionization and flames as well as for studying the flame propagation of marginally flammable materials. The conclusions note that bright emissions in nitrogen and helium are due to reactions among hydrofluorocarbon (HFC) fragments rather than oxidative combustion.

D. Clodic, **Diffusion of Flammables in Rooms Due to Leaks from Portable Air-Conditioners or Refrigerators Working with Propane or Isobutane**, unpublished presentation (International Conference on Ozone Protection Technologies, Washington, DC, 21-23 October 1996), École des Mines de Paris, France, October 1996 (12 pages with 26 figures and 3 tables, available from JMC as RDB6B03)

This paper presents tests of the spread of simulated leaks of R-290 and R-600a in an instrumented room. It examines localized concentrations for flammable gases that are denser than air, with specific attention to the leakage amount, flow rate, and air circulation. The study measured both the time and distance to ignition points as well as the possibility of secondary ignition of other materials. Tests were conducted with leaks from window air conditioners, inside and outside domestic freezers, and from a refrigerant container. The paper concludes that the lower flammability limit (LFL) of a dense gas can be locally exceeded with pooling effect near the floor, even when the quantity limits specified in safety standards (European EN-378 and ASHRAE Standard 15) are satisfied. It recommends that safety limits for flammable gases should consider absolute quantities and heats of combustion, rather than concentrations based on the full room volume.

W. J. De Coursey, N. Zubryckyj, and N. Yoshida, **Effects of Water Vapor Content on the Inflammable Limits of Ammonia-Oxygen-Nitrogen Mixtures**, *Canadian Journal of Chemical Engineering,* 40:203-209, 1962 (7 pages, RDB4B75)

R-717, LFL, UFL, flammability

T. W. Dekleva (ICI Klea), **Flammability Testing: Observations Related to HFC Systems**, presentation 2.5, *ARI Flammability Workshop - Summary and Proceedings* (Chicago, 8-9 March 1994), Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1994 (12 pages with 31 presentation charts, available from JMC as RDB4788)

These charts outline a presentation on flammability testing of hydrofluorocarbon (HFC) refrigerants. An introductory chart notes that ASTM E681 tests at 100 °C (212 °F) are conservative, but that reported results have differed and may not reflect real-world conditions. A chart summarizes sensitivity tests to test conditions and criteria, including vessel size, ignition sources, and test temperatures and pressures. Current practice and concerns are identified for visual determinations of flammability; definitions are given for "combustibility," "flammability," and "propagate." A chart itemizes factors affecting flammability, including stoichiometry changes with humidity and inerting agents, ignition energies, temperature, pressure, and vessel size. Stoichiometric effects are described and illustrated when the hydrogen to fluorine ration in an HFC are greater than or equal to 1, are less than one, or there is insufficient oxidant present. A series of charts examines effects of assumptions and variables on heat of combustion calculations. The paper shows the combustion reaction for R-134a, noting that the formation of molecular fluorine is unlikely even though prescribed for heat of combustion calculations by ANSI ASHRAE Standard 34-1992

T. W. Dekleva, A. A. Lindley (ICI Klea), and P. Powell (ICI Chemicals and Polymers, Limited), **Flammability and Reactivity of Select HFCs and Mixtures,** *ASHRAE Journal*, 35(12):40,42,44-47, December 1993 (6 pages with 2 figures and 3 tables, available from JMC as RDB4302)

This article provides information on the reactivity and flammability of fluorocarbon refrigerants. A table presents the temperatures at which reactivity begins, *T-onset*, and at which 50% of the flowing refrigerant is decomposed, *T-50%*. Data are presented for a nitrogen atmosphere with glass as a catalyst for R-11, R-12, R-32, R-113, R-123, R-124, R-125, R-134, and R-134a and with iron gauze, aluminum, and copper as catalysts for R-12 and R-134a. Data also are presented for reactivity in air (with oxygen) with glass and iron gauze as catalysts for R-12 and R-134a. The reactivities of R-12 and R-134a opposite aluminum are compared, based on the potential for exothermic reactions in chillers when impellers become unbalanced. The authors indicate that there appears to be little or no potential for a spontaneous exothermic halogenation reaction for R-134a with molten aluminum; no reactions are anticipated for R-134a with 2% magnesium alloys or for R-32. The article then addresses the test methods for flammability and provides definitions for combustibility, flammability, a critical flammability ratio (CFR). "Combustibility" describes the chemical process in which an oxidant is reacted rapidly with a fuel to decompose and liberate stored energy. "Flammability" describes a more specific situation in which the reaction is self sustaining and the flame propagates away from the ignition source. The article discusses flammability test methods, including ASTM E681-85 and the ignition-source modification of ANSI/ASHRAE Standard 34-1992. It discusses the influences and test vessel size, ignition source, pressure, and temperature. Flammability results are reported for R-32, R-125, and R-134a. A table compares flame limits of R-32 based on vessel size and ignition source using published and new data. Four figures map the flammable concentrations of R-134a with oxygen and nitrogen at 100 and 170 °C (212 and 338 °F) at atmospheric pressure, and for 170 °C (38 °F) at 345 and 690 kPa (50 and 100 psia). Ignition conditions are discussed for R-134a in air and compared to those for R-22. The article then addresses the flammability of R-32 blends. It defines the CFR as the percentage of nonflammable refrigerant required to just render a mixture nonflammable at specified temperature and pressure on dilution with air. Values are tabulated for binary blends or R-32/125 and R-32/134a for different vessel sizes. A methodology is illustrated for use in analyzing fractionation scenarios for blends. The study confirms the low reactivity of the hydrofluorocarbons (HFCs) addressed.

D. E. Douglas and F. J. Benz, **Lower and Upper Flammability Properties of Ammonia in Air at Reduced Pressures**, report TR-205-002, National Aeronautics and Space Administration (NASA), White Sands Test Facility, New Mexico, 1978 (RDB4B62)

R-717 (ammonia), LFL, UFL

N. N. Elias, **Ignition of High Speed Hydrocarbon Leaks from Car Air Conditioning,** B.E. thesis (School of Mechanical and Manufacturing Engineering), University of New South Wales, Sydney, Australia, 1996 (144 pages, rdb8358)

ignition of R-290/600a (50/50) and other hydrocarbons from use as refrigerants and consequent leakage into cars

D. L. Fenton, K. S. Chapman, R. D. Kelley, and A. S. Khan (Kansas State University, KSU), **Operating Characteristics of a Flare/Oxidizer for the Disposal of Ammonia from an Industrial Refrigeration Facility**, paper 3921 (682-RP), *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):463-475, 1995 (13 pages with 12 figures, RDB6351)

flame limits of R-717 combusted with methane, influences of naphthenic and paraffinic mineral oils as well as polyolester (POE) lubricants, effects of injection of liquid ammonia, measurements of ammonia, carbon dioxide, carbon monoxide, hydrocarbons, oxygen, and nitrous oxides in discharge

D. L. Fenton, A. S. Khan, R. D. Kelley, and K. S. Chapman (Kansas State University, KSU), **Combustion Characteristics Review of Ammonia-Air Mixtures**, paper 3922, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):476-485, 1995 (10 pages with 6 figures and 3 tables, RDB6352)

R-717; kinetics of reaction with air; survey of published flame limits (LFL and UFL); effects of pressure, temperature, diluents, ignition energy, and burning velocity; mists, droplets, and sprays; autoignition, thermal and explosion hazards

please see page 6 for ordering information

D. L. Fenton and K. S. Chapman (Kansas State University, KSU), **Combustion of Ammonia With and Without Oil Vapor,** final report for 682-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 20 May 1994 (RDB4B60)

This report presents a detailed study of the combustibility of ammonia refrigerant, R-717. The first part presents a literature review covering flammability limits, test methods, and the effects of pressure, temperature, inert gas diluents, ignition energy, and form (mists, droplets, or sprays). It also discusses the chemical kinetics of ammonia combustion. The second documents flammability determinations using the ASTM E681-85 standard test method, with attention to relative humidity and other test conditions. The third part describes the equipment, procedures, and findings for examination of ammonia flaring (oxidizing) for emergency releases. The last part addresses the influence of lubricating oil and ammonia liquid on the flammability limits. The study reports lower and upper flammability limits (LFL and UFL), based on published studies, of 14.8 and 33.5%, respectively. The flammability range based on tests was found to be 15.15-27.35% for dry air and for air at 50% relative humidity; the limits narrowed to 15.95-26.55 at 100% relative humidity. Lower pressures tended to narrow the flammability range, and the LFL decreases as temperature rises. The report outlines tests and problems encountered with use of "flow-through" system to simplify flammability testing. Data are provided on ammonia flammability in air mixtures with unidentified naphthenic and paraffinic mineral oils, a polyolester (POE) lubricant, an experimental lubricant, and natural gas (methane). A 10% lubricant to ammonia weight ratio of naphthenic oil reduces the LFL to below 12% and 30% mixtures with paraffinic oil or POE reduce the LFL to approximately 8%. Oil concentrations exceeding 20% slightly reduce the UFL, while 30% POE reduces the UFL by nearly 5%. Injection of liquid ammonia into a near stoichiometric air-natural gas pilot flame at ammonia-to-natural mass ratios of less than 0.5 yielded ammonia exhaust concentrations less than 5 ppm. As the mass ratio increases, the ammonia concentration in the exhaust stream increases to over 6000 ppm before the flame extinguishes under stable flame conditions.

F. Fedorko, L. G. Frederick, and J. G. Hansel, **Flammability Characteristics of Chlorodifluoromethane (R-22)-Oxygen-Nitrogen Mixtures,** paper 3097, *Transactions* (Annual Meeting, Nashville, TN, 27 June - 1 July 1987), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 93(2):716-724, 1987 (9 pages with 4 figures and 1 table, rdb3A13)

flammability, LFL, UFL, heat of reaction

G. H. Goble (Purdue University), C. J. Dahn (Safety Consulting Engineers, Incorporated), B. Hardaway (Bill's Heating and Air Conditioning), and R. H. Miller (Peoples Welding Supply, Incorporated), **Some Safety Studies of a Ternary Refrigerant,** *Proceedings of the 1994 International Refrigeration Conference at Purdue,* edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 165-169, July 1994 (5 pages with 2 figures and 2 tables, available from JMC as RDB4822)

R-406A [R-22/600a/142b (55/4/41)], fractionation, flammability

W. Goetzler, L. Bendixen, and P. Bartholomew (Arthur D. Little, Incorporated, ADL), **Risk Assessment of HFC-32/HFC-134a (30/70) in Residential Unitary Heat Pumps**, seminar presentation (ASHRAE Winter Meeting, San Francisco, CA, 17-21 January 1998), report DOE/CE/23810-93B, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 20 January 1998 (16 pages consisting of presentation charts with 3 figures and 6 tables, available from JMC as RDB8503)

charts summarize a risk assessment of R-32/134a (30/70) in a 17.6 kW (5 ton), air-to-air, residential heat pump with attention to the background, information gathering, small- and large-scale testing, a fault tree analysis, and conclusions; charts note current use of hydrocarbon refrigerants in Europe, notably in refrigerators in Germany, packaged air conditioners manufactured in Italy, and ductless air conditioners produced in the UK; document identifies potential ignition sources and test findings; also summarizes full-scale room tests to map the concentrations of simulated refrigerant leaks and to ignite the leaked refrigerant; outlines nine fault tree scenarios; summarizes preliminary estimates of the number of added fires per unit per year due to operation and due to servicing as well as each of them with mitigation measures

W. Goetzler, L. Bendixen, and P. Bartholomew (Arthur D. Little, Incorporated, ADL), **Risk Assessment of HFC-32/HFC-134a (30/70 wt. %) in Split-System Residential Heat Pumps**, report DOE/CE/23810-92, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, April 1998 (162 pages with 39 figures and 23 tables, available from JMC as RDB8603)

risk assessment of R-32 and R-32/134a (30/70) in a 17.6 kW (5 ton), air-to-air, residential heat pump; includes an appended report of small-scale, laboratory tests of various ignition sources; also appends a report on full-scale room testing to characterize the diffusion of leaked refrigerant and the ability to ignite the leaked refrigerants; presents a fault-tree analysis to assess the risk in a typical American home, accounting for geographical differences in installation configurations; concludes that the risk due to fires from substitution of R-32 for R-22 in U.S. air conditioners would result in approximately 200 additional fires per year; notes that the risk is higher in the south based on the practice of enclosing air air-handlers in closets; also concludes that the risk with use of R-32/134a (30/70) is approximately 20% lower than for R-32 alone; report contrasts these estimates with statistics on U.S. fires noting that approximately 114,000 residential fires per year are attributed to heating systems; report also notes that the results presented "cannot be generalized to more flammable refrigerants such as hydrocarbons"

D. P. Grob (Underwriters Laboratories, Incorporated), **Safety Requirements for a Refrigerator That May Use a Flammable Refrigerant,** paper 7.2-2, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 174-180, December 1994 (7 pages with 1 table, RDB5432)

flammability, blends, fractionation, safety

D. P. Grob (Underwriters Laboratories, Incorporated), **Barriers in the U.S.A. to Using Propane as a Refrigerant**, *R-22 and R-502 Alternatives* (Proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 19-20 August 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 109-114, 1994 (6 pages, RDB4526)

W. L. Grosshandler, M. Donnelly, and C. Womeldorf (National Institute of Standards and Technology, NIST), **Lean Flammability Limit as a Fundamental Refrigerant Property (Phase III)**, report DOE/-CE/23810-98, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, August 1998 (126 pages with 58 figures and 6 tables, available from JMC as RDB9301)

This report summarizes continuing research to examine the potential for use of a counter-flow burner to accurately measure the flammability limits of refrigerants. Prior phases of the project (see RDB5601 and RDB7103) addressed the feasibility of using this approach to determine the lean or lower flammability limit (LFL) and critical flammability ratio (CFR). The current report addresses the sensitivity of the measured LFL to changes in burner design, burner modifications to operate at elevated temperatures to accommodate refrigerants with high boiling points, and design of a simple burner for use by industry and other laboratories. The report notes that the most significant design variable affecting the LFL is the burner diameter. It provides test results for the LFL and upper flammability limit (UFL) of R-32, the flammable range of R-245ca, and the CFR of R-32/125. The report reviews prior studies of premixed, counter-flow flames, describes the current counter-flow apparatus and operating procedures, presents experimental results, and recommends further activities to develop a method for assessing the flammability of refrigerants.

G. F. P. Harris and P. E. MacDermott, **Flammability and Explosibility of Ammonia**, *Institute of Chemical Engineering Symposium*, University of Manchester Institute of Science Technology, UK, 49:31-39, 1977 (9 pages, RDB6358)

R-717, flammability limits, explosivity, LFL, UFL

E. W. Heinonen and R. E. Tapscott (New Mexico Engineering Research Institute, NMERI), **Methods Development for Measuring and Classifying Flammability/Combustibility of Refrigerants**, presentation (ARI Alternative Refrigerants Evaluation Program, AREP, Meeting, Chicago, IL, 27 January 1995), report DOE/CE/23810-52A, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, January 1995 (20 pages with 3 figures and 1 table, available from JMC as RDB5254; photograph reproductions are of poor quality)

These document comprises presentation charts summarizing research to develop procedures and equipment to measure refrigerant flammability. A second objective is to characterize parameters affecting flammability. The charts outline three tasks, to gather and review available data, establish a test plan, and perform laboratory testing; each task is described. The first includes performance of a structured literature search, development of an information storage system named REFLIBRY, and preparation of an annotated bibliography and summary. REFLIBRY is described as a database with more than 100 entries covering flammability, ignition, and refrigerants. The second task used the information found, to identify data shortfalls and to design experiments and methods to address them. Nine parameters affecting flammability are noted, including apparatus size and construction, composition of the refrigerant, humidity, pressure, temperature, ignition type and strength, turbulence, component mixing, and altitude. The summary of the testing task addresses the data acquisition system (DAS); ASTM E681 flask and enclosure; ignition system; blends of R-32, R-125, R-134a; data analysis; and development of recommendations. The

DAS is described and both the E681 apparatus and NMERI explosion sphere are shown. The ignition source investigation and tests are outlined, and a plot illustrates the flammability sensitivity of R-32/125 to concentration, humidity, and temperature. The presentation concludes that starting pressure, and therefore altitude, has a significant effect, illustrated with tabular data for R-32/134a, and that flammability can be measured by a pressure increase. The charts outline recommendations to improve E681 tests and for further research.

E. W. Heinonen, R. E. Tapscott, and F. R. Crawford (New Mexico Engineering Research Institute, NMERI), **Methods Development for Measuring and Classifying Flammability/Combustibility of Refrigerants: Task 3 - Laboratory Test Results**, report DOE/CE/23810-50 also identified as NMERI 1994/44, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, December 1994 (96 pages with 30 figures and 17 tables, available from JMC as RDB5A18)

This report summarizes an investigation of the flammability characteristics of selected blends of refrigerants R-32, R-125, and R-134a using both a novel and conventional measurement methods. A detailed introduction reviews definitions of flammability and the lower and upper flammability limits (LFL and UFL). It also identifies indications of flammability beyond visual and presents the parameters that affect flammability. They include the ignition source, temperature and pressure of the mixture, humidity of the air, size and shape of the test vessel, test vessel materials, turbulence, concentration of the test gas, reactivity and mixing of the components, and altitude and resulting barometric pressure. The report then discusses and schematically illustrates the NMERI explosion sphere and an ASTM E681 test flask. It outlines the data reduction methodology and presents test results for R-32, R-125, R-134a, and blends of them. An analysis of the data examines the sensitivity to the cited parameters. The report presents conclusions regarding the effects of these influences. It recommends procedures for use of both the explosion and E681 apparatus as well as for future study of the effects of humidity and altitude and improvement of the explosion sphere method. It concludes that the method of determining flammability using ASTM E681 is marginally adequate, but can be improved, and that both it and use of the explosion sphere have their own niches for testing. Appendices present the data acquisition instructions, apparatus operating instructions, and tabular test results.

N. Kalkert and H. G. Schecker, **Determination of Explosion Limits of Ammonia in Mixtures with Simple Hydrocarbons and Air,** *German Chemical Engineering,* 3:53-56, 1980 (4 pages, rdb6354)

R-717, flame limits

O. Kataoka, M. Yoshizawa, H. Ohnishi, and S. Ishida (Daikin Industries, Limited, Japan), **Flammability Evaluation of HFC-32 and HFC-32/134a Under Practical Operating Conditions,** *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 33-38, July 1996 (6 pages with 9 figures and 2 tables, RDB6754)

R-32, R-32/134a (35/65), (40/60), and (60/40): flammability, diffusion analysis, combustion under practical conditions; concludes that the combustion behavior of refrigerants is very different under practical conditions than in small-scale (e.g., ASTM E-681) tests

F. J. Keller, L. Sullivan, and H. Liang (Carrier Corporation), **Assessment of Propane in North American Residential Air Conditioning**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 39-44, July 1996 (6 pages with 6 figures and 2 table, RDB6755)

comparison of R-290 with R-22 and R-410A in systems using safety measures, in a blend of R-290/227ea (70/30), and with a indirect (secondary-loop) heat transfer circuit; system considerations; simulated performance; direct and indirect global warming impacts (TEWI); flammability in manufacturing; concludes that the system with safety features to address flammability offers the best performance and lowest TEWI, but requires a 30% increase in cost; the same cost premium can lower TEWI if spent to increase the efficiency of an R-410A system

A. S. Khan, R. D. Kelley, K. S. Chapman, and D. L. Fenton (Kansas State University, KSU), **Flammability Limits of Ammonia-Air Mixtures**, paper 3920 (682-RP), *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):454-462, 1995 (9 pages with 6 figures, RDB6350)

R-717, flame limits: measured LFL-UFL = 15.15-27.35% in dry air and 15.95-26.55% at 100% relative humidity

M. M. Khan and J. L. Chaffee (Factory Mutual Research Corporation, FMRC), **Large-Scale Flammability Tests for Risk Assessment of A2 Refrigerants in a Split System Residential Heat Pump**, report J.I. 0D0R7.MT (appended to report DOE/-CE/23810-92), Air-Conditioning and Refrigeration

Technology Institute (ARTI), Arlington, VA, April 1998 (60 pages with 28 figures and 3 tables, RDB8605; available from JMC as part of RDB8603)

laboratory tests to evaluate the dispersion and ignition characteristics of R-32 and R-32/134a (60/40) [representing the worst-cast of fractionation composition for a nominal 30/70 blend] for likely leak scenarios for a residential, split-system, air-to-air heat pump: documents both concentration mapping from leaks to characterize the size, location, and dynamic behavior of the flammable zone and tests for ignition by selected means in the flammable zones; tests simulated leaks into a room in a quiescent environment, to the outdoors, from the indoor heat exchanger inside the air handler, and into a utility closet; found that slow releases into a room without air flow produced flammable concentrations that persisted for approximately 3 hr in a large portion of the room; catastrophic releases or air movement by a small fan caused enough mixing to reduce concentrations below the lower flammability limit (LFL); leaks into the air handler did not produce flammable concentrations within the air handler where electrical components are located, but a fast leak with the fan off produced flammable concentrations near the floor where the refrigerant leaked out of the air handler; fan operation resulted in concentration dilution to below the LFL in supply ducts

R. A. Kingsbury (Underwriters Laboratories Incorporated, UL), **ASTM E681: A Sound Basis for Flammability Testing of Alternative Refrigerants**, presentation 2.1, *ARI Flammability Workshop - Summary and Proceedings* (Chicago, 8-9 March 1994), Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1994 (10 pages with 7 presentation charts, available from JMC as RDB4784)

These charts recap a presentation of the flammability test procedure prescribed in ASTM E681-85. A schematic diagram illustrates the apparatus used for tests. The charts outline discussion of applicability for gases, liquids, and solids - including those that are volatile under test conditions for the latter two - and the ignition sources used. They may include an electrical spark, exploding copper wire, or (as required by ANSI/ASHRAE Standard 34-1992 for halocarbon refrigerants) an electrically-activated kitchen match head. A chart indicates as advantages that the tests are reproducible, temperature is easily controlled, and humidity or inerting gases can be added. Another cites as disadvantages that it is a "small" test, flame propagation is sometimes difficult to see, and tests may not reflect real-world conditions. A final chart indicates that the prescribed method is a controlled laboratory test, but not a risk assessment.

V. N. Krivulin, L. A. Lovachev, E. Z. Kudryavtsev, and A. N. Baratov, **Study of Flammability Limits I, Ammonia-Air Mixtures,** *Fiz. Goreniya Vzryva,* 11(6):890-897, 1975 (8 pages, RDB6359)

R-717, flammability limits, LFL, UFL

W. Leuckel, B. Leisenheimer, and K. Bier (Universität Karlsruhe, Germany), **Verbrennungstechnische Eigenschaften des Kältemittels R152a und seiner Mischungen mit R134a beziehungsweise R32** [Flammability of Refrigerants R-152a and its Mixtures with R-134a or R-32], *Ki Klima-Kälte-Heizung,* Germany, 20:113-117, April 1992 (5 pages, in German, RDB4528)

R-134a/152a, R-32/152a, combustibility

A. A. Lindley, **Klea® 134a Flammability Characteristics at High Temperatures and Pressures**, ICI Chemicals and Polymers, Wilmington, DE, undated circa 1993 (9 pages with 4 figures, RDB4A01)

This document summarizes tests of R-134a to gauge the effects of temperature and pressure on its flammability. The document defines the terminology used, including flammability, upper and lower flammability limits, and combustion. It describes an autoclave used for the tests and comments on the effects of vessel size and the ignition source used. Flammability diagrams are provided for R-134a with nitrogen and oxygen at 100 °C (212 °F) and 103 kPa (15 psia) and at 170 °C (338 °F, reported as 388 °F) and 103, 345, and 689 kPa (15, 50, and 100 psia). The document concludes that R-134a is not flammable at atmospheric pressure at temperatures up to at least 170 °C (338 °F). It estimates that a minimum pressure of 483-517 kPa (70-75 psia) would be required to achieve flammability at 170 °C (338 °F, reported as 388 °F), with a narrow range of flame limits (8-12% R-134a by volume), in air for the vessel size used. It cautions that mixtures of R-134a with air should not be used for pressure leak testing and that the decomposition products of R-134a are irritating and highly toxic. It also recommends use of breathing apparatus if R-134a is exposed to fire conditions.

J. F. Missenden, R. W. James, and A. K. H. Wong, **Propane for Systems with Small Refrigerant Charge,** *Proceedings of the Franco, Swedish Conference of AICVF,* France, March 1990 (RDB-5556)

R-290, safety, flammability

H. Onishi (Daikin Industries, Limited, Japan), **The Current Status and Remain**[ing] **Issues for Eval-**

uation of Refrigerant Safety, paper 7.1, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 163-167, December 1994 (5 pages with 2 figures and 3 tables; in Japanese with abstract and figures in English; RDB5430)

R-22, R-32, R-125, R-134a, R-143a, R-152a, R-32/134a (30/70), ozone depletion potential (ODP), global warming potential (GWP), flammability

H. Onishi (Daikin Industries, Limited, Japan), **Flammability Evaluation Method for High LFL Substances**, presentation 2.6, *ARI Flammability Workshop - Summary and Proceedings* (Chicago, 8-9 March 1994), Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1994 (8 pages with 6 presentation charts, available from JMC as RDB-4789)

H. Ohnishi, N. Izutani, S. Inagaki, K. Karasawa, S. Ishida, and O. Kataoka (Daikin Industries, Limited, Japan), **Relationship Between Flammability and Composition Ratio of HFC-32/HFC-134a Blend**, *R-22 and R-502 Alternatives* (Proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 19-20 August 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 115-125, 1994 (11 pages with 15 figures and 6 tables, RDB4527)

R-32/134a, R-32/125/134a

P. R. Reed and J. J. Rizzo (E. I. duPont de Nemours and Company), **Combustibility and Stability Studies of CFC Substitutes with Simulated Motor Failure in Hermetic Refrigeration Equipment**, paper 152, *New Challenges in Refrigeration* (proceedings of the XVIIIth International Congress of Refrigeration, Montreal, Québec, Canada, 10-17 August 1991), International Institute of Refrigeration, Paris, France, II:888-891, August 1991 (4 pages with 1 figure and 2 tables, RDB3A11)

The paper summarizes a study to determine if alternative refrigerants become combustible when sufficient air is present, the mixture is heated and/or pressurized, and a suitable ignition source is provided. It cites prior studies (see RDB3A12 and RDB3A13) that document similar effects for R-22 and other refrigerants containing hydrogen. The paper illustrates and explains the experimental apparatus used and describes the test procedures. A table summarizes a matrix of tests for different ratios of air, temperatures, and pressures. The refrigerants tested included R-11, R-12, R-123, R-134a, R-22/152a/114 (36/24/40) (DuPont MP30), and R-22/152a/124 (36/24/124) (DuPont MP33). A second table provides lower and upper vapor combustibility limits for R-134a in air at temperatures of 16-177 °C (61-351 °F) and absolute pressures of 40-2122 (6-308 psi). The document indicates that all of the tested refrigerants were noncombustible with 0-2% air by volume and 82-177 °C (180-351 °F). The authors conclude that all fluorocarbons containing hydrogen will result in combustible mixtures with sufficient air at some temperatures and pressures. R-134a exhibited combustion at elevated pressures when air exceeded 80% and the blends did likewise when air exceeded 80% at elevated temperatures at any pressure. The paper notes the combustion products pose no undue hazard and that most equipment would stop working with the high air ratios required.

W. R. Rolingson, J. MacPherson, P. D. Montgomery, and B. L. Williams, **Effect of Temperature on the Upper Flammable Limit of Methane, Ammonia, and Air Mixtures,** *Journal of Chemical and Engineering Data*, (5):349-351, 1960 (3 pages, RDB6203)

R-50, R-717, flammability limits, LFL, UFL

R. W. Sesterhenn (Underwriters Laboratories Incorporated, UL), **Flammability Testing of Refrigerants 32 and 32/134a**, report 97NK5683, NC2523 (appended to report DOE/CE/23810-92), Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, April 1998 (23 pages with 5 tables, RDB8604; available from JMC as part of RDB8603)

laboratory tests of R-32 and R-32/134a (60/40) ignition to assess flammability risks in the event of a leak; concludes that these refrigerants can be ignited by sources such as high-voltage arcs, an abnormally hot wire such as a heating element or from breaking an incandescent light bulb, an open flame, and a compressor contactor (relay) breaking an abnormally high current; also concludes that R-32 can be ignited by a spark at 120 or 240 V with high currents; R-32 was not ignited by operation of wall switches, motors, an electric drill, a halogen light bulb, a low-voltage arc, or the spark from 120 V at usual current

I. R. Shankland (AlliedSignal Incorporated), **Some Issues Related to Flammability Classification of Refrigerants, or When is a Refrigerant Flammable? How Flammable is Flammable?**, publication unknown, 1993 (rdb4A05)

J. J. Shepherd, **Ammonia Flares: Costs, Codes, Installation and Design Considerations**, *Technical Papers of the 12th Annual Meeting* (Memphis, TN, 4-7 March 1990), International Institute of Ammonia Refrigeration (IIAR), Washington, DC, 111-125, March 1990 (RDB6360)

R-717

H. N. Sherbo, A. Y. Korolchenko, O. Y. Eremenko, S. G. Tsarickenko, and V. Navtshenya, **Concentration Limits of Flammability in Vapor-Gas Mixtures Based on Halohydrocarbons,** *Zhurnal Fizicheskoi Khimiii* [Journal of Physical Chemistry], Russia, 64(5):1327-1331, 1991 (5 pages probably in Russian, RDB4C55)

refrigerant flammability

C. Rajasekariah, **Hydrocarbon Refrigerant Safety in Automobiles**, B.E. thesis (School of Mechanical and Manufacturing Engineering), University of New South Wales, Sydney, Australia, 1995 (140 pages, rdb8359)

use of R-290/600a (50/50) and other hydrocarbons as refrigerants in mobile air-conditioning (MAC) systems

V. Razmovski, **Safety of Hydrocarbon Refrigerants for Car Air-Conditioning Systems**, B.E. thesis (School of Mechanical and Manufacturing Engineering), University of New South Wales, Sydney, Australia, 1994 (97 pages, rdb8360)

use of R-290/600a (50/50) and other hydrocarbons as refrigerants in mobile air-conditioning (MAC) systems

R. G. Richard (AlliedSignal Incorporated), **Refrigerant Flammability Testing in Large Volume Vessels (Flammability Criterion Determination for ASTM E681, Visual Observations)**, report DOE/CE/23810-87, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, March 1998 (12 pages with 4 figures and 2 tables, available from JMC as RDB8403)

This report addresses flammability test methods for refrigerants that are difficult to ignite. It focuses on the influence of combustion vessel size on the appearance of the flame. In doing so, it examines the criteria to determine whether a flame will propagate through a uniform mixture, how a flame that just propagates by a proposed test protocol appears, and the angle and size of that flame. The study measured the flame characteristics for two blends, R-134a/152a and R-125/152a, each formulated in varied proportions. The tests were repeated in 12 and 200 L (0.42 and 7.1 ft^3) vessels to validate a proposed flame cap angle criterion of $\pi/2$ rad (90°) for the smaller vessel for halocarbons. The report concludes that the proposed $\pi/2$ rad (90°) "fan" (subtended arc) criterion is appropriate to determine flame propagation in the ASTM Standard E681 test method with spark ignition for the most conservative conditions in 12 L (0.42 ft^3) vessels. The report also notes the tests for the blends studied were sensitive to humidity. The report cites, without elaboration, determination of a critical flammability ratio (CFR) of 33.4 ± 1.2% m/m R-32 for R-32/134a in air from a round-robin test with an unspecified number of laboratories.

R. G. Richard and I. R. Shankland (AlliedSignal Incorporated), **Flammability of Alternative Refrigerants**, *ASHRAE Journal,* 34(4):20,22-24, April 1992 (4 pages with 1 figure and 5 tables, RDB2525)

This article reports data for refrigerant flammability measurements using the ASTM E681 test procedure. Lower and upper flame limits (LFL and UFL) are tabulated for R-11, R-22, R-30 (methylene chloride), R-32, R-50 (methane), R-113, R-123, R-123a, R-124, R-125, R-134, R-134a, R-140a, R-141b, R-142b, R-143, R-143a, R-152, R-152a, R-161, R-E170 (dimethyl ether), R-218, R-290 (propane), R-C318, R-600 (butane), R-600a (isobutane), R-611 (methyl formate), R-717 (ammonia), and R-7146 (sulfur hexafluoride). The flammability test procedure and apparatus are discussed, including attention to the ignition source, based on recommendations of ASHRAE Standard 34-1992. Flammability limits are compared for R-32, R-141b, and R-142b, to illustrate the influence of alternative ignition sources and conditions. Critical flammability ratios are presented for selected mixtures.

W. V. Richards (William V. Richards Incorporated), **Design and Installation of Large Ammonia Systems**, presentation 5.2, *ARI Flammability Workshop - Summary and Proceedings* (Chicago, 8-9 March 1994), Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1994 (10 pages with 3 presentation charts, available from JMC as RDB4796)

R-717

J. J. Rizzo (DuPont Fluoroproducts), **Flammability Testing and Vapor Fractionation Issues in Blends**, presentation 3.2, *ARI Flammability Workshop - Summary and Proceedings* (Chicago, 8-9 March 1994), Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1994 (8 pages with 6 presentation charts, available from JMC as RDB-4791)

W. A. Rosser, H. Wise, and J. Miller, **Mechanism of Combustion Inhibition by Compounds Containing Halogens**, *Proceedings of the Seventh International Symposium on Combustion,* Butterworth-Heinemann, Limited, London, UK, 175-182, 1959 (RDB4B66)

please see page 6 for ordering information

J. R. Sand and D. L. Andrjeski (The Trane Company), **Combustibility of Chlorodifluoromethane,** *ASHRAE Journal*, 24(5):38-40, May 1982 (3 pages with 1 figure and 4 tables, RDB3A12)

This article summarizes laboratory tests of the combustibility of pressurized mixtures containing R-22 and air or oxygen, prompted by a fatal industrial explosion. The article reviews prior flammability testing of R-22 and presents thermochemical calculations, using heats of formation, heat capacities, and postulated products. These calculations show that an exothermic reaction between R-22 and air is theoretically possible. The experimental apparatus and procedures used are described followed by discussion of the results. The article notes inconsistencies in the data, which are summarized in a table, and attributes them to vessel geometry, volume-to-surface ratio, ignition influences. Combustion test data for oxygen/R-22 mixtures are tabulated and plotted. The highest heats of combustion appear for mixtures containing 25-40 mole % R-22. These results are compared to predicted stoichiometric values and testing observations. Comparative heats of combustion (HOC) are presented for R-22, R-50 (methane), R-20 (chloroform), and R-20I3 (iodoform). The HOC values given are ~419, 844, 373, and 678 MJ/kg·mol (180,000, 380,000, 160,000, and 291,000 Btu/Ib·mol), respectively, for the four gases. Combustion products also are listed for air/R-22 and oxygen/R-22 mixtures, though the article notes that identification was distorted by contaminants from reactions between resultant acids and the sample bags used. The authors conclude that pressurized mixtures of R-22 and air containing at least 50% air are combustible. The heat generated by this reaction is capable of increasing the pressure in a closed container by 6-8 times, but large activation energies are necessary for initiation. Tests of R-11 and R-12 mixtures with oxygen found them not combustible under similar conditions.

I. R. Shankland (AlliedSignal Incorporated), **Flammability, Fractionation, and Test Conditions**, presentation 3.1, *ARI Flammability Workshop - Summary and Proceedings* (Chicago, 8-9 March 1994), Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1994 (20 pages with 17 presentation charts, available from JMC as RDB4790)

H. Shaoqiang, L. Xiaoping, and X. Chunfei (Wanbao Refrigerator Industrial Corporation, China), **Refrigerant HFC-152a Flammability Test Results**, publication unknown, undated circa 1991 (4 pages with 1 table, available from JMC as RDB2512)

This paper assesses the flammability risk of R-152a, which is reported as flammable in concentrations of 4.7-16.8% by volume in air. The authors hypothesized that the highest probability of fires and explosions will occur when enough refrigerant leaked from the freezer evaporator into the fresh-food compartment, with ignition caused by an arc or spark from the thermostat. Concentrations of 5, 10, 15, and 20% R-152a were tested using an electric pulse spark. Ignition was found to be unlikely in the model tested (BCD-158), because of incomplete mixing and the location of the thermostat. The risk would be high in a frost-free refrigerator, requiring an explosion-proof thermostat. The paper concludes that the most likely scenario for a fire is when the concentration reaches 12% and is exposed to an open flame. A person standing near the refrigerator could be injured by a blow from the door opened by fire or explosion, by flames, or both. No deformation or damage to the refrigerator cabinet was observed from test fires.

H. W. Sibley (Carrier Corporation), untitled keynote address (presentation 1.1), *ARI Flammability Workshop - Summary and Proceedings* (Chicago, 8-9 March 1994), Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1994 (7 pages, available from JMC as RDB4782)

N. D. Smith (U.S. Environmental Protection Agency, EPA) and M. W. Tufts (Acurex Environmental Corporation), **Flammable Properties of HFC Refrigerants - Some Fundamental Considerations,** presentation 2.2, *ARI Flammability Work*shop - *Summary and Proceedings* (Chicago, 8-9 March 1994), Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1994 (24 pages with 22 presentation charts, available from JMC as RDB-4785)

These presentation charts review fundamental considerations for flammability of hydrofluorocarbon (HFC) refrigerants and offer recommendations on test and ranking methods. The first illustrates the effect of moisture on the flammability of R-245ca and R-245fa, indicating increasing flammability rank with increasing relative humidity, up to approximately 60%. A table lists the combustion reactions and changes in Gibbs free energy and enthalpy (heat) of combustion (HOC) for R-32, R-50, R-143, R-143a, R-152, R-152a, R-170, and R-290. Two more give the same data, reactions with moisture present, and moisture dependence for R-134a, R-227ea, R-236ea, R-245ca, R-245fa. Tables then show the stoichiometric compositions, ranges between lower and upper flammability limits (LFL and UFL), weighted free energy, HOC, and LFL for the cited refrigerants. A plot shows the HOC dependence of refrigerant concentrations in oxygen for R-32, R-134a, R-152a, and R-245fa. A chart outlines the role of an oxidizing free radical in combustion kinetics. A table and plot show the reaction rate constants at 25 °C (-4 °F), resultant LFL, and relative rate of combustion versus refrigerant concentration. A table and plot suggest and illustrate a flammability ranking dependent on the free energy, reaction rate, and stoichiometric ratio. Another table shows that this ranking is inversely related to the extent of fluorination for hydrofluorocarbon (HFC) refrigerants. The flammability ranges for R-32, R-152a, R-245ca, and R-245fa are plotted as functions of their concentrations in air and the concentration of R-134a as a suppressant. A chart summarizes the chemistry of suppression, listing bromine, chlorine, iodine, and the CF_3 radicals as free radical (OH) scavengers A table gives the ideal gas heat capacities by mole and by weight for the HFCs addressed plus R-125, R-134, R-143, and R-227ca. Another table outlines selection of optimum HFC flammability suppressants. The presentation charts then summarize experimental ranking factors as the lowest concentration in air which results in flame propagation (LFL), range of LFL to UFL, amount of energy released, ease of ignition, and rate of pressure rise or maximum pressure. The conclusions note that all HFCs are potentially combustible, those having fewer hydrogen than fluorine atoms may involve water as a reactant, and that insufficient water is available in air for complete combustion. Further, stoichiometric fuel/air compositions yield the highest HOC, but not necessarily the highest reaction rate. Relative flammabilities can be calculated for screening purposes, molecular criteria for decreasing flammability can predict when refrigerants are nonflammable at normal conditions, and refinement of the ASTM E681 test method should be considered. The presentation provides recommendations for experimental determinations of flammabilities of refrigerants, fire hazard risk determinations, and clarification of flammability limits via the ASTM E681 method.

E. S. Starkman and G. S. Samuelson, **Flame-Propagation Rates in Ammonia-Air Combustion at High Pressure,** *Proceedings of the Eleventh International Symposium on Combustion,* Butterworth-Heinemann, Limited, London, UK, 1037-1045, 1967 (8 pages, RDB6356)

R-717

D. W. Treadwell (Lennox Industries Incorporated), **Packaged Air-Conditioning Equipment Employing Propane,** presentation 5.3, *ARI Flammability Workshop - Summary and Proceedings* (Chicago, 8-9 March 1994), Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1994 (42 pages with 39 presentation charts, available from JMC as RDB-4797)

R-290

Y. Urano, S. Horiguchi, K. Tokuhashi, M. Iwasaka, and S. Kondo, **Flammability Limits of Alternative Refrigerants,** *Koatsu Gasu* [High Pressure Gases], Japan, 27(6):22-28, April 1990 (7 pages, in Japanese, RDB5648)

LFL, UFL

R. J. M. van Gerwen, M. Verwoerd, and P. A. Oostendorp (Netherlands Organization for Applied Scientific Research, TNO, The Netherlands), **Flammable Refrigerants,** *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlagsund Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 8, 1999 (6 pages with 1 figure and 2 tables, RDB9841)

summarizes quantitative risk analyses (QRA) for hydrocarbon (HC) refrigerants for a bulk milk tank and for a residential heat pump; applies two criteria, namely individual risk (IR) and societal or group risk (GR), considering normal operating conditions, maintenance and repair activities, and application dependent activities; concludes that the risks of these applications are acceptable as are those for other applications with charges "up to a few kilograms"; discusses European development of standards on risk levels; notes that attention is needed to training and certification of the technicians servicing the equipment

K. S. Willson and W. O. Walker (Ansul Chemical Company), **Flammability Limits in Air ... Methyl Chloride and Mixtures of Methyl Chloride with Dichlorodifluoromethane**, *Industrial and Engineering Chemistry,* 36(5):466-468, May 1944 (3 pages with 2 figures and 1 table, RDB6633)

R-40, LFL-UFL (8.0-18.9% v/v), comparisons with different ignition sources (spark, cigar, cigarette, hot wire, match); R-12/40 (of interest due to R-12 shortages) found to be not flammable when the R-12 fraction is 10% or greater

A. K. H. Wong, **Some Implications of the Application of Propane in Domestic Refrigerators**, research memorandum 123, Institute of Environmental Engineering, South Bank University, London, UK, June 1989 (RDB5560)

R-290, safety, flammability

I. Yamaoka and H. Tsuji, **An Experimental Study of Flammability Limits Using Counterflow Flames**, *Seventeenth Symposium (International) on Combustion,* The Combustion Institute, 843 ff, 1979 (rdb9302)

please see page 6 for ordering information

flammability limits, LFL, UFL, test and measurement methods

ARI Flammability Workshop - Summary and Proceedings (Chicago, 8-9 March 1994), Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1994 (290 pages with summary and 16 sets of presentation charts, available from ARI; RDB4781)

Flammability Characteristics of Isotron 141b, preliminary information bulletin, Elf Atochem North America, Incorporated (provided by the former Pennwalt Corporation), King of Prussia, PA, May 1989 (1 page, available from JMC as RDB0521)

Lower and upper flammability limits (LFL and UFL), as a volume percentage of refrigerant in humid air, are given for R-141b based on ASTM E681 tests. The limits cited are 7.4-15.5% at 21 °C (70 °F) and 5.8-16.5% at 120 °C (250 °F). The maximum explosion pressure and maximum rate of pressure rise are tabulated for the same temperatures. Flammability characteristics of ethyl alcohol and R-290 (propane) are presented for comparison. A higher concentration of R-141b is required for flammability. Additionally, R-141b exhibits significantly lower rates of pressure rise and lower heats of combustion.

Guide to Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids, publication 325, National Fire Protection Association (NFPA), Quincy, MA, 1994 (RDB6710)

flammability data

Results of Testing: Limits of Flammability for Isotron 142b, preliminary information bulletin, Elf Atochem North America, Incorporated (provided by the former Pennwalt Corporation), King of Prussia, PA, May 1989 (4 pages, available from JMC as RDB0526, picture missing)

Lower and upper flammability limits (LFL and UFL), as a volume percentage of refrigerant in humid air, are given for R-142b based on ASTM E681 tests. The LFL cited is 7.8% at 21 °C (70 °F) using a fuse wire as the ignition source. The cited LFL and UFL, using a match as the ignition source, are 6.9-17.0% at 21 °C (70 °F) and 6.1-17.8% at 120 °C (250 °F). Comparative data are presented for R-600a (isobutane) and ethanol, 1.86-8.5% and 3.46-18.4% respectively. A modified test procedure and the method of determining flammability limits are presented. Additionally, the effects of humidity, temperature, and ignition source on flammability testing are discussed.

Standard for Refrigerants, standard 2182, Underwriters Laboratories Incorporated (UL), Northbrook, IL, 30 December 1994 (18 pages with no figures or tables, RDB5216)

This standard contains test procedures and methods to evaluate and categorize refrigerants according to their extent of flammability. The refrigerants covered are intended for use in air-conditioning and refrigeration equipment. The standard comprises a scope defining applicability and exclusions (e.g., efficiency, physiological effects, and toxicity), units of measure, definitions, and sections on flammability rating, storage containers, fractionation analysis, flammability testing, and autoignition temperature tests. Refrigerants that exhibit no flame limits (i.e., do not propagate a flame at 100 °C, 212 °F) and additionally do not have an autoignition temperature less than 750 °C (1382 °F) are categorized as "nonflammable." Those with no flame limits but having an autoignition temperature less than 750 °C (1382 °F) are categorized as "practically nonflammable." Refrigerants that propagate a flame are classed as "flammable." The standard prescribes test procedures and conditions to determine the flame limits, measure the autoignition temperature, and categorize blends considering both their as-blended and worst-case fractionated conditions. It also details a procedure to simulate leakage as well as charge and recharge cycles for testing azeotropic and zeotropic blends. A final section specifies requirements for container markings, including manufacturer and refrigerant identities, fire-hazard ratings, and orientation or liquid-phase charging warnings.

Standard Test Method of Autoignition Temperature of Chemicals, standard E659-78, American Society of Testing and Materials (ASTM), West Conshohocken, PA, 1978, reapproved in 1989 (rdb2920)

Standard Test Method for Concentration Limits of Flammability of Chemicals, standard E681-94, American Society of Testing and Materials (ASTM), West Conshohocken, PA, 1994 (RDB5810)

flammability limits, LFL, UFL

Standard Test Method for Determining Limits of Flammability of Chemicals at Elevated Temperature and Pressure, standard E918-83, American Society of Testing and Materials (ASTM), West Conshohocken, PA, 1983, reapproved in 1988 (rdb2922)

flammability limits, LFL, UFL

Standard Test Method for Minimum Ignition Energy and Quenching Distance in Gaseous Mixtures, standard E582-76, American Society of Testing and Materials (ASTM), West Conshohocken, PA, 1976, reapproved in 1981 (RDB2921)

Reactivity

Aerodyne Research, Incorporated, **Heterogeneous Chemistry of Alternate CFC Oxidation Intermediates with HCFC-21 and Other Chemicals,** report EPA 86-920001060 (OTS0544334), Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), Washington, DC, 31 July 1992 (RDB5968)

R-21, R-125 and others, reactivity, environmental impacts

C. Chiorboli (possibly C. Chiorbolic) et al., **Application of Chemometrics to the Screening of Hazardous Substances: Part II. Advances in the Multivariate Characterization and Reactivity Modelling of Haloalkanes**, *Chemometrics Intelligent Laboratory Systems*, 19(3):331-336, 1993 (4 pages, rdb5969)

R-125 and others, reactivity

P. V. Mitin, V. G. Barabanov, and G. V. Volkov, **Kinetics of the Thermal Decomposition of 1-1-Difluoro-1-chloroethane and 1,1,1-Trifluoroethane**, *Kinet. Katal.,* 29(6):1468-1470, 1988; translation by Cytech Languages, Incorporated, 11 October 1989 (6 pages with 2 figures and 1 table, RDB6A03)

R-142b, R-143a: studies of the thermal kinetics for decomposition in continuous flow systems reveal significant discrepancies based on methods and effects of reactor walls; compares the kinetic reaction parameters with those measured by other investigators

J. Sehested et al., **A Kinetic Study of the Reaction of Fluorine Atoms with Fluoromethane, Chloromethane, Bromomethane, Difluoromethane, Carbon Monoxide, Trifluoromethane, 2,2-Dichloro-1,1,1-trifluoromethane, 1,1,1,3- and 1,1,2,2-Tetrafluoropropane, 1-Chloro-1,1-difluoroethane, 1,1-Difluoroethane, and Pentafluoroethane at 295 ± 2 K**, *International Journal of Chemical Kinetics*, 25(8):651-665, 1993 (14 pages, RDB5963)

R-23, R-40B1, R-41, R-32, R-141b, R-123, R-125, R-254cb, R-254fb, R-152a

TEST AND ANALYSIS METHODS

A. Abdul-Razzak, M. Shoukri, and J-S. Chang (McMaster University, Canada), **Measurement of Two-Phase Refrigerant Liquid-Vapor Mass Flow Rate - Part I: Venturi and Void Fraction Meters**, paper 3926, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):511-522, 1995 (12 pages with 11 figures, RDB6364)

refrigerant mass-flow rate, instrumentation

A. Abdul-Razzak, M. Shoukri, and J-S. Chang (McMaster University, Canada), **Measurement of Two-Phase Refrigerant Liquid-Vapor Mass Flow Rate - Part II: Turbine and Void Fraction Meters**, paper 3927, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):523-531, 1995 (9 pages with 10 figures and 1 table, RDB6365)

refrigerant mass-flow rate, instrumentation

A. Abdul-Razzak, M. Shoukri, and J-S. Chang (McMaster University, Canada), **Measurement of Two-Phase Refrigerant Liquid-Vapor Mass Flow Rate - Part III: Combined Turbine and Venturi Meters and Comparison with Other Methods**, paper 3928, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):532-538, 1995 (7 pages with 7 figures, RDB6366)

refrigerant mass-flow rate, instrumentation

M. W. Abel (Integral Sciences, Incorporated, ISI), **Organic Contaminant Determination of Refrigerant Blends**, seminar presentation (ASHRAE Winter Meeting, San Francisco, CA, 17-21 January 1998), report DOE/CE/23810-93C, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 20 January 1998 (14 pages consisting of 25 presentation charts with 2 figures, available from JMC as RDB8504)

Charts present new gas chromatography (GC) methods, intended for adoption as standards, to determine the organic purity of zeotropic and azeotropic refrigerants. Methods cover R-401A, R-401B, R-401C, R-402A, R-402B, R-404A, R-405A, R-406A, R-407A, R-407B, R-407C, R-407D, R-408A, R-409A, R-409B, R-410A, R-410B, R-411A, R-411B, R-412A, R-500, R-502, R-503, R-507A, R-508A, and R-509A. The presentation summarizes the capabilities of the methods as well as requirements for both testing and calibration. It concludes that blend analysis is not difficult and can be performed with common instruments. It further notes that preparation of the calibration standard is more difficult, and that accuracy is measurable but dependent on the lab performing the work.

M. Arnemann, **Methoden zur Bestimmung Thermophysikalischer Eigenschaften von Öl-Kältemittel-Gemischen** [Methods to Determine Thermophysical Properties of Oil-Refrigerant Mixtures],

dissertation, Universität Hannover, Hannover, Germany, circa 1996 (in German, RDB4532)

refrigerant-lubricant properties

M. J. Assael, C. M. B. P. Oliveira, M. Papadaki, and W. A. Wakeham, **Vibrating-Wire Viscometers for Liquids at High Pressures,** *International Journal of Thermophysics,* 13(4):593-615, 1992 (13 pages, RDB4883)

J. P. Balaresque and S. Grabeuil (Dehon Services, France), **A User-Friendly Software for Computations of Vapor Compression Cycles with Pure Fluids and Zeotropic Mixtures**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 223-228, July 1996 (6 pages with no figures or tables, RDB6906)

basic equations and computation methods to calculate thermodynamic and transport properties for single-compound, azeotropic, and zeotropic refrigerants; analysis model for one- and two-stage cycles; description of microcomputer program

T. J. Bruno, **Accelerated Identification of Alternative Refrigerant Products with Standard Chromatographic Retention Parameters**, unpublished seminar presentation charts (Winter Meeting of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, ASHRAE, Chicago, 28 January - 1 February 1995), National Institute of Standards and Technology (NIST), Boulder, CO, 1995 (26 pages with 12 figures and 1 table, available from JMC as RDB5343)

A set of charts address methods to provide fast, reliable identification of alternative refrigerant products and contaminants with low cost, simple techniques. The method provides for optimization of more sophisticated quantitative analyses. Charts summarize and illustrate a database of information of fluorocarbon spectrography, chromatography, physical properties, and safety. A table compares the information content and costs for identification techniques, including mass spectrometry, infrared spectrophotometry, ultraviolet spectrophotometry, nuclear magnetic resonance, refractive index, and gas chromatography. Further charts outline the limitations of and illustrate resolution measures for gas chromatography. Sample data are presented for R-13, R-14, R-21, R-22, R-23, R-32, R-40, R-41, R-114, R-114a, R-114B1, R-115, R-116, R-123, R-124, R-125, R-133a, R-134, R-134a, R-141b, R-142b, R-143, R-143a, R-152a, R-160, R-161, R-215aa, R-215ba, R-216ba, R-217ba, R-217caB1, R-225ca, R-225cb, R-227ca, R-227ea, R-236ea, R-243db, R-245ca, R-245cb, R-245fa, R-236fa, R-253fb, R-262da, R-263fb, R-270aa, R-270da, R-270fa, R-243db, R-270fb, R-280da, R-1112a, R-1112c, R-1112t, R-1113, R-1122, R-1122B1, R-1123, R-1131a, R-1132a, R-1140B1, R-1141, and R-1243. The report identifies a database in preparation for field use to facilitate analyses.

T. J. Bruno (National Institute of Standards and Technology, NIST), **Chemical Analysis Protocol for Alternative Refrigerants - Part 1: Spectroscopic Methods**, paper 3618, *Transactions* (Annual Meeting, Baltimore, MD, June 1992), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 98(2):204-209, 1992 (6 pages with 2 figures and 1 table, RDB2603)

T. J. Bruno (National Institute of Standards and Technology, NIST), **Chemical Analysis Protocol for Alternative Refrigerants - Part 2: Separation Methods**, paper 3619, *Transactions* (Annual Meeting, Baltimore, MD, June 1992), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 98(2):210-215, 1992 (6 pages with 7 figures, RDB2604)

T. J. Bruno, **Spectroscopic Library for Alternative Refrigerant Analysis**, report NIST Special Publication 794, National Institute of Standards and Technology, Boulder, CO, August 1990 (192 pages, available from GPO as stock number 003-003-03036-8 for $12.00 prepaid, RDB2250)

This report assembles infrared and mass spectra on a range of ethane and ethylene compounds relevant to research of alternative refrigerants. Limited physical property and safety data also are included. Some compounds addressed are not suited for refrigerant use, but could be found as impurities or as reaction/decomposition products in refrigerant tests. This publication provides an information source to aid in identification of such compounds. The ethane compounds addressed include R-112, R-112a, R-113, R-113B2, R-113a, R-114, R-114a, R-114B2, R-115, R-116, R-121, R-122, R-123, R-123B1, R-123B2, R-123aB1, R-124, R-125, R-131, R-131a, R-132b, R-132bB2, R-133a, R-133aB1, R-134, R-134a, R-141, R-141b, R-142B1, R-142b, R-143, R-143a, R-151B1, R-152a, and R-161. Ethylene compounds covered include R-1110, R-1111, R-1112a, R-1112aB2, R-1113, R-1114, R-1120, R-1121, R-1122B1, R-1123, R-1130, R-1130, R-1130a, R-1131a, R-1132a, and R-1141.

J. J. Byrne, M. W. Abel, and A. M. Gbur (Integral Sciences, Incorporated, ISI), **Methods Development for Organic Contaminant Determination in Fluorocarbon Refrigerant Azeotropes and**

Blends, report DOE/CE/23810-85, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 3 March 1998 (156 pages with 34 figures and 35 tables, available from JMC as RDB8505)

Report presents new gas chromatography (GC) methods to determine the organic purity of zeotropic and azeotropic refrigerants. Appendices patterned after those in ARI Standard 700 Appendix 95 identify columns, chromatographic conditions, and methods to determine both the composition and purity of covered blends. They address those in the 401, 402, 404, 405, 406, 407, 408, 409, 410, 411, 412, 500, 502, 503, 507, 508, and 509 refrigerant series following the designations assigned in ANSI/ASHRAE Standard 34. They include R-401A, R-401B, R-401C, R-402A, R-402B, R-404A, R-405A, R-406A, R-407A, R-407B, R-407C, R-407D, R-408A, R-409A, R-409B, R-410A, R-410B, R-411A, R-411B, R412A, R-500, R-502, R-503, R-507A, R-508A, R-508B, and R-509A. The new methods are applicable to both new and reclaimed refrigerants. The report identifies procedural improvements, clarifications, limitations, and recommendations for future additions.

A. P. Cohen (UOP), **Test Methods for the Compatibility of Desiccants with Alternative Refrigerants,** paper 3662, *Transactions* (Winter Meeting, Chicago, IL, 23-27 January 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(1):408-412, 1993 (5 pages with 8 figures and 1 table, RDB4669)

This paper presents a method for testing the compatibility of desiccants with alternative refrigerants and associated lubricants. The paper notes that the standard sealed-tube test, following ASHRAE Standard 97-1989, does not hold a sufficient sample to properly characterize desiccants. The new method involves exposure of the materials in a stainless steel cylinder, shown in a photograph. The paper discusses the methods of testing the properties of the exposed desiccants for water content, water capacity, halogen content; crush strength, and attrition resistance. A table summarizes the specific methods along with the required sample mass, precision, and representative ranges of values. The paper shows schematics of the apparatus for each test.

C. Cusano, H. K. Yoon, and C. H. Poppe (University of Illinois at Urbana-Champaign), **Accelerated Screening Methods for Predicting Lubricant Performance in Refrigerant Compressors - Final Report,** report DOE/CE/23810-45, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, November 1994 (160 pages with 84 figures and 80 tables, available from JMC as RDB-5109)

This report summarizes research to improve screening methods for lubricants for air-conditioning and refrigeration compressors. It compares data obtained with a high pressure tribometer (HPT) and those by other methods. The report reviews the general requirements for simulative, specimen testing. It also discusses problems encountered in scaling and test acceleration, the latter by increasing the load or speed to obtain measurable wear in a short period of time. The report notes drawbacks in popular methods, such as Falex™ testing and compressor bench tests. The bulk of the report is divided into two parts, the first of which compares HPT data to those obtained by three compressor manufacturers using Falex machines. The specimen data, test parameters, and refrigerant-lubricant combinations are tabulated. Tests were performed using grey cast iron (GCI) with SAE 333 die cast aluminum, SAE 356 die cast aluminum with hardened drill rod, and SAE 380 die cast aluminum and grey cast iron with carburized 1018 steel. The friction and wear data are plotted, typical wear scars shown, and resulting rankings of lubricants are compared to those for three combinations of load and speed with the HPT. The tests employed R-134a and R-32/125/134a (30/10/60) with unidentified polyolester (POE) lubricants as well as R-12 and R-22 with mineral oils. Part II compares accelerated wear data for specific components, supplied by five manufacturers, to data obtained with the HPT and with a Four Ball tester using chrome-alloy steel (AISI E-52100) balls. The HPT tests used SAE 380 die cast aluminum, carburized 1018 steel, ductile cast iron, and sintered ferrous pins and plates paired and tested to approximate the manufacturer tests. The wear data and lubricant rankings are again tabulated and typical wear scars shown. The tests used R-12 and R-22 with mineral oils, R-22 with two alkylbenzenes, and R-134a with 12 different ester lubricants. Additional tests were performed with the HPT and Four Ball devices in lubricant-air environments, to examine the effects on friction and wear. The report concludes that the lubricant rankings for the conventional and HPT tests are not very good except when a lubricant resulted in relatively large wear. Moreover, the HPT tests conducted in lubricant-air environments yielded results unlike those conducted in pressurized refrigerant environments. While the authors note that the data obtained do not give a clear vision about the development of a new bench test method, they suggest that the HPT is likely to be an improvement based on use of the refrigerant environment. An appendix describes and schemati-

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cally illustrates the HPT, Falex, and Four Ball testers. The HPT is characterized as representing the temperature and pressure environment found in specific contact points in compressors. Further appendices outline the experimental procedures, measurements, and calculations and summarize the raw data in tables. A final appendix provides references on refrigerant compressor lubrication.

E. S. Domalski and E. D. Hearing, **Estimation of Thermodynamic Properties of C-H-N-O-S-Halogen Compounds at 298.15 K**, *Journal of Physical and Chemical Reference Data*, 22(4):805-1159, 1993 (355 pages, rdb5727)

CFC, HCFC, HFC, FC, thermodynamic properties, thermophysical data

P. A. Domanski (National Institute of Standards and Technology, NIST), **EVAP5M**, supplement to report DOE/CE/23810-81, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 20 December 1996 (1 3½" computer disk, available from JMC - use 22 pages to determine cost - as RDB7862)

EVAP5M simulates the performance of finned-tube evaporators with R-22 or R-407C operating with one-dimensionally maldistributed air: input data consists of evaporator design data, interactive selection between R-22 and R-407C, and operating conditions (from a data file or interactively); default input files are provided; output includes total and latent heat capacity, outlet refrigerant parameters at the outlet of individual heat exchanger circuits, outlet air conditions; supplied model is a compiled version from Fortran source code (not included) for execution on DOS and Windows® systems; model incorporates thermophysical property data from NIST REFPROP version 5.01; see RDB7861 for the User's Manual, which includes data samples and screen captures to illustrate the program [Windows is a registered trademarks of Microsoft Corporation]

P. A. Domanski and M. O. McLinden (National Institute of Standards and Technology, NIST), **A Simplified Cycle Simulation Model for the Performance Rating of Refrigerants and Refrigerant Mixtures,** *International Journal of Refrigeration* (IJR), 15(2):81-88, February 1992 (8 pages with 6 figures and 1 table, RDB3448)

A. P. Duvedi and L. E. K. Achenie (University of Connecticut), **Designing Environmentally Safe Refrigerants Using Mathematical Programming,** *Chemical Engineering Sciences*, 51(15):3727-3739, 1996 (13 pages with 1 figure and 10 tables, RDB-7701)

strategy for computer-aided molecular design (CAMD) to identify or develop refrigerants with desired properties, by optimizing the influences of selected structural groups: applies a mixed integer, nonlinear programming method to predictive functions for the normal boiling point, vapor pressure, ozone depletion potential (ODP), theoretical compressor displacement, mass flow, and refrigerating effect; summarizes case studies to find replacements

P. F. Ellis II, K. T. Fuentes, and A. F. Ferguson (Radian International LLC), **The Simulated Stator Unit (SSU) Test - An Improved Accelerated Hermetic Motor Insulation Life Test**, presentation (EM & CW '98, Cincinnati, OH, 6-8 October 1998); republished as report DOE/CE/23810-99A, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 1998 (22 pages with 22 presentation charts including 4 figures and 1 table, available from JMC as RDB8B43)

This series of presentation charts presents a proposed test method to predict the life of motor insulation materials in hermetic motors for compressors for air-conditioning and refrigeration equipment. The tests of a simulated stator unit (SSU) incorporate features of the IEEE 117 motorette test, UL 984 insulation test, and plug reversal tests. It provides a full simulation of electromechanical and thermomechanical forces acting on the stator of a hermetic motor under stalled rotor conditions for 20,000 repetitions per 24 hr period. The charts review the need and advantages of the proposed method, the history of its development, the test conditions, and discrimination and reproducibility of tests. The presentation concludes that the test method is ready for commercial application and will be in the public domain.

P. F. Ellis II, A. F. Ferguson, and K. T. Fuentes (Radian International LLC), **Accelerated Test Methods for Life Prediction of Hermetic Motor Insulation Systems Exposed to Alternative Refrigerant-Lubricant Mixtures, Phase 3: Reproducibility and Discrimination Testing**, final report DOE/CE/23810-69 (DCN 96-660-030-04), Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 6 May 1996 (52 pages with 16 figures and 4 tables, available from JMC as RDB-6806)

This report presents tests of a simulated stator unit (SSU) to predict the life of motor insulation materials in hermetic motors for air-conditioning and refrigeration equipment. The SSU consists of a laminated electrical steel core simulating the stator stack of a motor. The report recaps development of the SSU and test method as well as earlier proof-of-concept testing (see RDB3A17 and RDB5649). The report describes and illustrates the SSU, its control and data acquisition system, and test procedures. It then summarizes the objectives and preparatory activities for the subject tests, discusses changes in interpretation of capacitance and power dissipation factor results, and outlines the test environment. It details the charging procedures for both a baseline case with R-22 and mineral oil and a test case with deliberately added contaminants. The latter, identified as an "aggressive refrigerant trial," comprises an R-22-oil mixture with five times the refrigerant contaminants allowed under ARI Standard 700-93. The report then presents the test results and explains rejection of 6 of the 14 tests performed, based on apparatus and/or instrumentation failures. It then outlines an analysis of events-to-failure data, post failure conditions, and insulation property measurement (IPM) data. A series of plots shows the IPM results. The report concludes that these tests show a life difference, based on median surges-to-failure measurements, between the baseline R-22/oil mixture and the aggressive refrigerant/lubricant. It discusses changes in the test method and recommendations for future relocation of the winding core temperature thermocouple.

P. F. Ellis II, A. F. Ferguson, and K. T. Fuentes (Radian Corporation), **An Improved Accelerated Hermetic Motor Insulation Life Test**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 181-185, July 1996 (5 pages with 3 figures and 1 table, RDB6837)

describes development and validation of a test method, identified as the Simulated Stator Unit (SSU) test, for motor insulation systems that combines the IEEE motorette and standardized plug-reversal tests; provides data from tests with R-22 and mineral oil, both with and without added air, moisture, and hydrochloric acid

P. F. Ellis II and A. F. Ferguson (Radian Corporation), **Accelerated Test Methods for Predicting the Life of Motor Materials Exposed to Refrigerant-Lubricant Mixtures, Phase 2: Proof of Concept Demonstration,** final report DOE/CE/23810-57 (DCN 94-660-030-02), Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 19 April 1995 (68 pages with 13 figures and 5 tables, available from JMC as RDB5649)

This report reviews development and proof-of-concept tests of a simulated stator unit (SSU) to predict the life of motor insulation materials in hermetic motors for air-conditioning and refrigeration equipment. The report recaps a survey of failure modes in hermetic motor insulation and implications for an accelerated life test. It outlines three current test methods and compares them in a table. The report reviews the conceptual design (see RDB3A17) of the SSU and advantages over the IEEE 117 Motorette test. It then describes a prototype test unit, a control and data acquisition system, and test procedures. A detailed table compares the conceptual and as-built prototype designs. It describes the tests and illustrates sample measurements. A table presents the test results for three prototypes. One was tested without thermal stress loads, to demonstrate that the insulation property measurements themselves do not degrade the SSU. The other two were subjected to 20,600 simulated locked-rotor events per day. Both showed progressive deterioration and one suffered a coil-to-coil failure, one of the anticipated failure modes. The report describes a future phase of the study, to answer specific engineering/design questions, incorporate refinements, and examine repeatability and viability of the SSU test concept.

P. F. Ellis II and A. F. Ferguson (Radian Corporation), **Accelerated Test Methods for Predicting the Life of Motor Materials Exposed to Refrigerant-Lubricant Mixtures**, final report DOE/CE/-23810-21, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, August 1993 (68 pages with 13 figures and 4 tables, available from JMC as RDB3A17)

P. F. Ellis II (Radian Corporation), **Accelerated Test Methods for Predicting the Life of Motor Materials Exposed to Refrigerant-Lubricant Mixtures, Phase I: Conceptual Design**, seminar presentation (ASHRAE Winter Meeting, New Orleans, LA, January 1994), report DOE/CE/23810-32, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 24 January 1994 (26 pages with 22 charts, available from JMC as RDB4212)

This report comprises presentation charts summarizing a study to develop an accelerated test method, to predict the life of motor materials exposed to refrigerant-lubricant mixtures. The charts outline the objectives, namely to conduct a literature search and surveys to identify causes of hermetic motor failures and test methods for insulation for hermetic compressor motors. A further objective is to propose a conceptual test design. Several charts identify failure causes, 76.6% of which were electrical and 89.9% of them involved stator windings. The charts outline the mechanisms of failure and tests currently used in motor development. They include the IEEE Standard 117 and UL Standard 984 motorette tests and a plug-reversal test. The charts outline each of them along with identified advantages and weaknesses.

The charts then summarize a simulated stator unit (SSU) device and test method; the SSU is shown in a figure. The anticipated results and advantages of the new approach are listed. The charts conclude with a status summary, indicating completion of the conceptual design and consideration of a prototype as a proof-of-concept demonstration.

J. E. Field, **Method for Determining Refrigerant and Lubricant Decomposition for HFCs and POEs Using Ion Chromatography**, unpublished seminar presentation charts (Winter Meeting of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, ASHRAE, Chicago, 28 January - 1 February 1995), Spauschus Associates, Incorporated, Stockbridge, GA, 1995 (16 pages with 7 figures and 1 table, available from JMC as RDB5347)

11 presentation charts and notes; hydrofluorocarbon refrigerants, polyolester lubricants, refrigerant and lubricant decomposition after aging in sealed tubes

D. G. Gehring (National Refrigerants), **How to Determine Concentration of Water in System Refrigerants**, *ASHRAE Journal*, 37(9):52-53,55, September 1995 (3 pages with 2 figures, limited copies available from JMC as RDB5934)

This article discusses the relevance of moisture presence in air-conditioning and refrigeration systems, noting that "water is the single most deleterious contaminant" in a system. It identifies recommended concentration limits both in new refrigerants and lubricants. It then discusses sampling and analysis sensitivity to the phase of the sample. A representative calculation shows that higher accuracy can be obtained using liquid-phase samples The article discusses other parameters and suggests that sampling temperature is virtually insignificant. Two figures correlate the liquid phase fraction to total water in the vapor phase and to water increase in the liquid phase. As shown, the water content from a sample taken from the liquid phase gives nearly the correct concentration of water, provided the container from which the sample is drawn is at least 75% filled with the liquid. The paper also discusses the influence of other parameters, including wall adsorption of moisture, surface coatings that lead to hydrate formation, and hydrolysis reactions with impurities or lubricant additives. The paper explains why water is sometimes visible when an analysis does not reflect it. This discrepancy is attributed to the slow rate at which water dissolves in refrigerant. The paper stresses the importance of using clean sampling and measuring devices to avoid analyses that show higher than actual water content.

R. E. Kauffman (University of Dayton Research Institute), **Accelerated Screening Methods for Determining Chemical and Thermal Stability of Refrigerant-Lubricant Mixtures, Part II: Experimental Comparison and Verification of Methods**, report DOE/CE/23810-41 volume I, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, September 1995 (134 pages with 70 figures and 18 tables, available from JMC as RDB-6201)

This report summarizes an investigation of analytical techniques for development of an accelerated method of compatibility testing. The resulting method was designed to be safe and to produce chemical and thermal stability rankings that are consistent with those from conventional thermal-aging tests, independent of refrigerant-lubricant compositions, and suited for a wide variety of materials. The work expands on earlier screening of techniques [see RDB3501] that found in situ measurement of electrical conductivity to be the most suitable. The present report presents data from sealed-tube tests, performed in accordance with ANSI/ASHRAE Standard 97-1989, for R-12, R-22, R-134a, and R-32/134a (30/70) with lubricants and valve-steel catalysts. The specimens were aged at 175 °C (347 °F) for four weeks; the R-12 samples were aged only for two weeks. Comparative data using the conductivity screening method, for up to one-week at the same temperature, also are presented. Additional data are provided for ramped temperatures from 175-205 °C (347-401 °F) for R-12, R-22, and R-134a and lubricants, with and without steel catalysts, and for R-22 with additized polyolester lubricants. The report concludes that there is some agreement between the methods and that the new method may be more sensitive to degradation. It cautions that the new approach should be viewed as a supplement rather than a replacement for conventional methods, pending further testing and evaluation. An appendix shows the gas chromatograms for the pretest and aged refrigerant-lubricant mixtures. A second provides plots of in situ conductivity measurements for the refrigerant-lubricant mixtures. A third appendix describes determination of the volatile degradation product fraction. A final appendix identifies the lubricant samples, which included a naphthenic mineral oil (Witco Suniso® 3GS), two paraffinic mineral oils (Penreco Sontex 160LT and 200LT), an alkylbenzene (Shrieve Zerol® 150), two polyglycols (Dow P-425 and ICI Emkarox® RL 118D), and four polyolesters (POEs). The POEs include two pentaerythritol ester mixed acids (ICI Emkarate™ RL 22H and Mobil EAL Arctic® 22A) and two pentaerythritol ester branched acids (Henkel Emery® 2928 and Castrol Icematic® SW32). The refrigerant specimens were obtained from PCR Incorporated.

R. E. Kauffman (University of Dayton Research Institute), **Accelerated Screening Methods for Determining Chemical and Thermal Stability of Refrigerant-Lubricant Mixtures, Part II: Experimental Comparison and Verification of Methods**, report DOE/CE/23810-41 volume II, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, September 1995 (1 3½" computer disk accompanied by an 8 page report with 1 table, available from JMC - use 28 pages to determine cost - as RDB6202)

This report provides supporting data from an investigation of analytical techniques to develop an accelerated method of compatibility testing. The resulting method was designed to be safe and to produce chemical and thermal stability rankings that are consistent with those from conventional thermal-aging tests, independent of refrigerant-lubricant compositions, and suited for a wide variety of materials. The work expands on earlier screening of techniques that found in situ measurement of electrical conductivity to be the most suitable. This volume comprises a disk with measured data and a description of the data format.

R. E. Kauffman (University of Dayton Research Institute), **Accelerated Screening Methods for Determining Chemical and Thermal Stability of Refrigerant-Lubricant Mixtures, Part I: Method Assessment**, report DOE/CE/23810-10, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, April 1993 (42 pages with 2 figures and 1 table, available from JMC as RDB3501)

This report presents the results of a literature search. It addresses analytical techniques suitable for development into accelerated screening tests, to evaluate the chemical and thermal stabilities of refrigerant-lubricant combinations. The search focused on chemical stability data for R-12, R-22, R-134a, and other refrigerant candidates as well as thermal analytical techniques. The computerized search sources and approaches are summarized. Identified literature and prepared abstracts are categorized as analyses of chlorine-free refrigerants, analyses of chlorinated refrigerants, and accelerated thermal analytical techniques. Other documents are listed in an appendix. Evaluation criteria for candidate compatibility tests are indicated. Identified methods are discussed, and two differential thermal analytical (DTA) techniques are outlined for further development. Initial results are presented for one method for separate combinations of R-12 and R-22 with mineral oil. The candidate techniques will be evaluated in a second phase of the project.

L. Kettwich and D. P. Grob (Underwriters Laboratories, Incorporated), **Pressure Strength Test Requirements for Refrigerant Containing Parts Using Fatigue Analysis**, *The Earth Technologies Forum* (proceedings, Washington, DC, 26-28 October 1998), Alliance for Responsible Atmospheric Policy, Arlington, VA, 237-246, October 1998 (10 pages with 2 figures and 1 table, RDB8B20)

summarizes the need, development, and proposed procedure for cyclic testing for fatigue to qualify products using high pressure refrigerants without invoking the current safety factors (generally the higher of five times the maximum design pressure or three times potential abnormal pressures)

A. Laesecke (Universität Stuttgart), **Viskosität und Wärmeleitfähigkeit als thermodynamische Zustandsgrößen und ihre Darstellung durch Zustandsgleichungen** [Viscosity and Thermal Conductivity as Thermodynamic Properties and their Representation by Equations of State], *Fortschritt-Berichte VDI*, VDI-Verlag, Düsseldorf, Germany, 3(117), 1993 (rdb8467)

thermophysical data

J-Y. Lin and M. B. Pate (Iowa State University of Science and Technology), **A Methodology for Simultaneously Measuring Thermal Conductivity and Viscosity of Refrigerant Mixtures**, *Proceedings of the 1994 International Refrigeration Conference at Purdue*, edited by D. R. Tree and J. E. Braun, Purdue University, West Lafayette, IN, 43-48, July 1994 (6 pages with 2 tables, RDB4808)

J. J. Meyer and J. M. Saiz Jabardo (University of Illinois at Urbana-Champaign), **An Ultrasonic Device for Measuring the Oil Concentration in Flowing Liquid Refrigerant**, *International Journal of Refrigeration* (IJR), 17(7):481-486, September 1994 (6 pages with 11 figures, RDB4B72)

This article describes a pulse-echo technique and ultrasonic transducer developed for real-time, in place measurement of the acoustic velocity of flowing liquid refrigerant. Combined with temperature measurement, the results enable monitoring of oil concentrations in liquid refrigerants. The article reviews the principles, theory of operation, experimental set-up, and procedures used for verification. It also discusses transit-time measurements, pressure effects, and comparisons to prior research findings. Data were taken for R-12 with 0.0-10.64% by mass naphthenic mineral oils (Witco Suniso® 3GS and 5GS) and for R-134a with 0.0-9.11% unidentified, ester-based lubricant. The tests covered -22 to 40 °C (-8 to 104 °F).

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The predicted concentrations based on velocity and temperature measurements and deviations are plotted for water, R-12/mineral oil, and R-134a/ester-based lubricant. Analyses showed that the predicted oil concentration depends linearly on both speed of sound and temperature. Measured data are compared for the new method and the standard technique for determining oil concentration, using ASHRAE Standard 41.4-1984. Uncertainties were of the order of ¼% by weight at typical system concentrations. A slight dependence of acoustic velocity on pressure was found. The article notes that the technique addressed is limited to liquid-line measurements.

T. F. Morse (Hope Technologies Corporation), **Infrared Analysis of Refrigerant Mixtures**, report DOE/CE/23810-82, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 24 January 1998 (36 pages with 20 figures and 1 table, available from JMC as RDB8304)

summarizes tests to assess the viability of using intra-cavity laser spectroscopy to identify refrigerants; discusses use fiber laser intra-cavity spectroscopy (FLICS) in conjunction with the broad gain band width of a thulium fiber laser as a sensing technique; presents infrared (IR) absorption data in the range of 1.65-2.00 microns for R-12, R-22, R-32, R-115, R-124, R-125, R-134a, R-152a, R-404A, R-502, and mixtures of R-404A and R-502; concludes that further research is needed, but that the method will achieve detection within a few percent for the gases tested

F. T. Murphy (ICI Klea, UK), R. E. Low (ICI Klea, USA), S. Corr (ICI Klea, UK), and B. E. Gilbert (ICI Klea, USA), **Scaling Factors for Compressor Ratings Tables,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 96-106, October 1995 (11 pages with 6 figures and 3 tables, available from JMC as RDB5A50)

R-404A, R-407A, R-407B, R-507A: compressor performance, calorimetry rating tables, capacity correction, subcooling, extension to other suction gas temperatures and pressures

N. D. T. Rohatgi (Spauschus Associates, Incorporated), **Effects of Temperature on Desiccant Catalysis of Refrigerant and Lubricant Decompositions**, report DOE/CE/23810-95, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, June 1998 (74 pages with 16 figures and 12 tables, available from JMC as RDB8B42; some of the plots reproduce poorly in black-and-white photocopying; color copies are available for $39.00 additional)

This report summarizes tests and presents resulting plots and correlations to interpolate or extrapolate decomposition rates for refrigerants and lubricants from accelerated, thermal-aging tests. It notes that such tests generally are performed at high temperatures (149 °C, 300 °F) for short aging periods (28 days), but the temperatures are much lower and operating times much longer in actual use. The data and plots provided relate the decomposition rates to aging time, aging temperature, and type of desiccant. The report summarizes tests of 3Å and 4Å molecular sieves and of activated alumina from scale and from trihydrate with R-22 and mineral oil (MO, Witco Suniso® 3GS), R-32 with a mixed-acid polyolester (MA-POE, Castrol Icematic® SW32), and R-134a with a MA-POE. The refrigerant-lubricant (RL) combinations and desiccants were tested with steel, aluminum, and copper coupons as catalysts at 40, 60, 80, 100, and 120 °C (104, 140, 176, 212, and 248 °F) in sealed glass tubes. The aged specimens were evaluated for visual changes, lubricant total acid number (TAN), halide ions, and acid anions. The report notes that while there is no correlation between data from sealed-tube tests and actual performance in refrigeration systems, such tests are used to screen materials for compatibility. It concludes that the findings can be used to compare stability of desiccant-refrigerant-lubricant combinations at any reaction temperature, but that a criterion must be chosen for instability or incompatibility. No decomposition was found in the R-134a tests. Temperature is the most important variable in predicting decomposition, which is small below 80 °C (176 °F), at most 2% per year for R-22 and R-32. R-32 and desiccant combinations are more reactive and thus have shorter aging times than R-134a and desiccant combinations.

H. O. Spauschus (Spauschus Associates, Incorporated), G. Freeman, and T. L. Starr (Georgia Tech Research Institute, GTRI), **Surface Analysis of Glass from Sealed Tubes After Aging with HFC-134a,** presentation charts (ASHRAE Annual Meeting, Baltimore, MD, June 1992), Spauschus Associates, Incorporated, Atlanta, GA, USA, June 1992 (21 pages with 7 figures and 2 tables, available from JMC as RDB2729)

This presentation reported findings of an investigation of the sealed-tube test procedure. The study examined whether fluoride decomposition products formed in aging hydrofluorocarbons (HFCs) at high-temperature, react with the glass surface. The underlying concerns are that such reactions might destroy evidence of other chemical reactions and might also weaken the tubes, posing a safety risk. These concerns challenge the suitability of the ANSI/ASHRAE Standard 97-1989 test procedure for HFCs, and other refrigerants. The charts outline prior studies for and against fluoride attack of glass and an experiment to investigate the issue. Glass shards from sealed tubes, used in thermal aging tests, were examined by photoelectron spectrometer. No fluoride was detected from any tube except one treated with hydrofluoric acid (HF). The study concluded that R-134a undergoes neither thermal decomposition nor reactions with lubricants, metals, or glass at temperatures as high as 200 °C (392 °F). No evidence was found of fluoride formation in the absence of catalysts, such as molecular sieves. The study also concluded that borosilicate glass tubes are suited as reaction vessels for sealed-tube tests. (See RDB2217, RDB2326, RDB2327, RDB2329, and RDB2526 for related papers)

H. O. Spauschus and D. R. Henderson (Spauschus Associates, Incorporated), **New Methods of Determining Viscosity and Pressure of Refrigerant-Lubricant Mixtures,** *Proceedings of the 1990 USNC/IIR-Purdue Refrigeration Conference and ASHRAE-Purdue CFC Conference,* edited by D. R. Tree, Purdue University, West Lafayette, IN, 173-176, July 1990 (4 pages with 7 figures, 6 page preprint available from JMC as RDB2249)

This paper describes new methods for measuring viscosity and vapor pressure of refrigerant-lubricant mixtures for compositions of 0-100% and temperatures from -40 to 150 °C (-40 to 300 °F). The equipment and methods also can be applied to fluids for absorption systems. Automatic data acquisition, data reduction, and computer generated graphics are utilized. Typical viscosity-pressure-temperature-composition data are presented to illustrate engineering applicability. The method uses a new viscometer, based on electromagnetic forces and the time required for a metallic piston to traverse a known distance through the fluid.

S. Suzuki, Y. Fujisawa (Toyoda Automatic Loom Works, Japan), S. Nakasawa, and M. Matsuoka (CHINO Corporation, Japan), **Measuring Method of Oil Circulation Ratio Using Light Absorption**, paper 3663, *Transactions* (Winter Meeting, Chicago, IL, 23-27 January 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 99(1):413-421, 1993 (5 pages with 18 figures and discussion by A. E. Bergles, RDB7642)

test methods, refrigerant-lubricant ratios, oil circulation, illustrative tests with R-12 and a paraffinic mineral oil and for R-134a with a polyalkylene glycol (PAG)

H. K. Yoon, C. H. Poppe, and C. Cusano (University of Illinois at Urbana-Champaign), **Screening Lubricants for Refrigerant Compressors: A Comparison Between a Pin and Block Tester and the High-Pressure Tribometer,** paper 3907, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):322-334, 1995 (13 pages with 10 figures and 12 tables, RDB6330)

This paper summarizes research to improve screening methods for lubricants for air-conditioning and refrigeration compressors. It compares data obtained with a high pressure tribometer (HPT) and those by other methods. The paper notes drawbacks in popular methods, such as Falex™ testing and compressor bench tests. The specimen data, test parameters, and refrigerant-lubricant combinations are tabulated. The friction and wear data are plotted and resulting rankings of lubricants are compared to those for three combinations of load and speed with the HPT. The tests employed R-134a and R-32/125/134a (30/10/60) with unidentified polyolester (POE) lubricants as well as R-12 and R-22 with mineral oils.

H. L. Yu, R. Y Li (Shanghai Institute of Mechanical Engineering, China), and D. K. Chen (Concordia University, Canada), **Experimental Comparison on Performance of Rotary Compressors with Different HFC-134a Compatible Lubricants**, paper 3908, *Transactions* (Annual Meeting, San Diego, CA, 24-28 June 1995), American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(2):335-340, 1995 (6 pages with 5 figures and 3 tables, RDB6331)

R-134a with five unidentified lubricants compared to R-12 with mineral oil

Analytical Procedures for ARI Standard 700-95, Appendix C to ARI Standard 700, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1995 (226 pages with 50 figures and 40 tables, available from ARI for $60.00 to members and $120.00 to others, RDB6305)

This document identifies definitive test procedures to determine the quality of new, reclaimed, and/or repackaged refrigerants for use in new and existing refrigeration equipment. These procedures are identified as referee methods; users must be able to demonstrate that the results of alternative test procedures employed are equivalent. Information is provided on the sensitivity, precision, and accuracy of each method. The tests covered are for determination of acidity, water (moisture) by Karl Fischer coulometric titration, high boiling residue by volumetric and/or gravimetric measurement, visual particulate residue, chloride content by silver chloride precipitation, and noncondensable gas content by gas chro-

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matography (GC). The document also identifies GC procedures to determine the purity, and for blends the compositions, of R-11, R-12, R-13, R-22, R-23, R-32, R-113, R-114, R-123, R-124, R-125, R-134a, R-143a, R-401 series blends (R-22/152a/124), R-402 series blends (R-125/-290/22), R-404A (R-125/143a/134a (44/52/4)), R-407 series blends (R-32/125/134a), R-408A (R-125/143a/22 (7/46/7)), R-409A (R-22/124/142b (60/25/15)), R-410 series blends (R-32/125), R-500, R-502, R-503, and R-507 [R-507A]. It indicates that standard GC data are not available to determine the compositions of R-405 series blends (R-22/152a/142b/C318), R-406 series blends (R-22/600a/142b), R-411 series blends (R-1270/22/152a), R-412 series blends (R-22/218/142b), R-508 [R-508A], and R-509 [R-509A] .

A Standard Calorimeter Test Method for Flow Measurement of a Volatile Refrigerant, ANSI/-ASHRAE Standard 41.9-1988, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1988 (20 pages with 7 figures, available from ASHRAE for $12 to members and $18 to nonmembers, RDB5218)

This standard outlines recommended practices to measure the rate of flow of volatile refrigerants using a calorimeter. It is intended for use where the entire flow stream enters the calorimeter as a subcooled liquid and leaves as a superheated vapor or the reverse, identified as evaporator- and condenser-types, respectively. The standard defines the terminology used and calorimeter classifications. It also outlines requirements for values to be determined, standard and confirming test methods, test conditions, and safety. It then details the types and precisions of instruments and measurements, describes the apparatus, and test methods and procedures. Schematics show the instrumentation points. The standard identifies the data to be recorded and calculations to reduce the measured data to final values. An appendix illustrates how to calculate the uncertainty in mass flow rate for representative test conditions.

Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity), standard test method D445-85, American Society for Testing and Materials, West Conshohocken, PA, 1985 (RDB4353)

Methods of Testing Discharge Line Refrigerant-Oil Separators, ANSI/ASHRAE Standard 69-1990, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1990 (20 pages with 13 figures, available from ASHRAE for $13 to members and $19 to nonmembers, RDB5217)

This standard provides a uniform test method to determine the capability of a discharge-line oil separator to remove oil from refrigerant. It defines the terminology used, specifies the data required, specifies the calculations involved, and describes the equipment required for the test. A secondary purpose of the standard is to facilitate and encourage necessary research in this area, by providing two procedures for measurement of oil carryover. The first can be used for high concentrations (≥2500 ppm) with low oil-flow rates (≤7.5 l/min, ≤2 gpm), as in reciprocating-piston compressors, and does not require a chemical analysis. The second can be used for low concentrations and high oil-flow rates, as in oil-injected screw compressors, but requires an infrared spectrophotometer. Both methods are detailed and schematically illustrated. The standard describes the test methods, reviews equipment provisions, specifies the instrumentation requirements, identifies the data to be recorded, and provides calibrations procedures and methods to calculate the results.

Methods of Testing the Floc Point of Refrigerant Grade Oils, standard ANSI/ASHRAE 86-1983, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1989 (RDB3A07)

This standard outlines a uniform method for measuring the waxing tendency of oils in refrigeration systems. The floc point test is based on evaluation of the wax precipitation, at low temperatures, in a mixture containing 90% R-12 and 10% oil by volume. The results are intended for comparisons of different oils.

Refrigerant Extraction Test, Copeland Corporation, Sidney, OH, undated circa 1989 (4 pages with 1 table, available from JMC as RDB0005)

This procedure outlines a test to determine the amount of extractable residue in materials that are used in hermetic refrigerant system when exposed to refrigerant environments. Extractables are determined as the fraction of weight loss after exposure to evaporating refrigerant at elevated temperature and pressure. Charging data are provided for R-12, R-22, and R-502.

Refrigerant-Lubricant Soak Test, Copeland Corporation, Sidney, OH, undated circa 1989 (3 pages, available from JMC as RDB0007)

This procedure outlines a test to determine the effect of materials exposed to a refrigerant-lubricant mixture at operating conditions. The parameters determined are dimensional, including swell, and weight change; visual observations of decomposition also are addressed. The procedure described is based on thermal-aging in a pressure vessel, preceded and followed by measurements.

Sealed Glass Tube Method for Determining the Stability of Materials Used within Refrigeration Systems, product engineering specification ES23-138, Copeland Corporation, Sidney, OH, 11 May 1987 (10 pages with 1 figure and 2 tables, available from JMC as RDB0006)

This procedure outlines a sealed-tube test to rate the quality of lubricants with R-12. It is based on visual inspection of the oil and metal (steel and copper) test strips and the amount of reactivity, determined by gas chromatography, after thermal aging at 175 °C (347 °F) for 3- and 14-day periods.

Sealed Tube Method to Test the Chemical Stability of Material for Use within Refrigeration Systems, ANSI/ASHRAE Standard 97-1989, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1989 (RDB2251)

compatibility test procedure

Specifications for Fluorocarbon and Other Refrigerants, standard 700-95, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1995 (16 pages with 1 table, available from ARI for $10.00 to members and $20.00 to others, RDB6304)

This standard specifies acceptable levels of contaminants for fluorocarbon and other refrigerants, regardless of source (new, reclaimed, and/or repackaged). It is intended for the guidance of manufacturers, refrigerant reclaimers, repackagers, distributors, installers, servicemen, contractors, and consumers. It identifies purity requirements and determination procedures for acceptance or rejection of refrigerants, for both new and existing refrigeration and air-conditioning products. These refrigerants include R-11, R-12, R-13, R-22, R-23, R-32, R-113, R-114, R-123, R-124, R-125, R-134a, R-143a, R-401A, R-401B, R-402A, R-402R, R-404A, R-405A, R-406A, R-407A, R-407R, R-407C, R-408A, R-409A, R-410A, R-410R, R-411A, R-412A, R-500, R-502, R-503, R-507 [R-507A], R-508 [R-508A], and R-509 [R-509A]. It provides for characterization of refrigerants by gas chromatography and boiling point or boiling point range. It also addresses water (moisture), chloride, acidity, high boiling residue, particulates and solids, noncondensables, and impurities including other refrigerants. The standard outlines procedures of sampling, purity determination, and reporting. A table lists the physical properties and maximum contaminant levels for covered refrigerants. It addresses the boiling point, typical isomer content (including R-113a in R-113, R-114a in R-114, R-123a in R-123, R-124a in R-124, R-134 in R-134a, and R-143 in R-143a), and the cited impurities. An appendix, published separately, describes the test procedures to be used.

Standard Test Method for Foaming Characteristics of Lubricating Oils, standard D892-82, American Society of Testing and Materials (ASTM), West Conshohocken, PA, 1988 (RDB7636)

refrigerant-lubricant foamability, foam stability

Standard Method for Measurement of Proportion of Oil in Liquid Refrigerant, ANSI/ASHRAE Standard 41.4-1984, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1984 (8 pages with 2 figures and 1 table, available from ASHRAE for $13 to members and $19 to nonmembers, RDB2924)

This standard outlines a uniform experimental method to determine the concentration of oil, by weight, in single-phase solutions in liquid refrigerant. The standard defines the terminology used and describes the equipment required. Schematics show the sampling vessel and bleeder assembly used. The test procedure entails evacuation, weighing, sampling, and separation of the refrigerant from the oil for a minimum of three samples. The document identifies the data to be recorded and provides equations to calculate the results.

Standard Test Method for Wear Preventive Characteristics of Lubricating Fluid (Four Ball Method), standard D4172-82, American Society of Testing and Materials (ASTM), West Conshohocken, PA, 1982 (rdb2923)

lubricant screening procedure

Test Method for Organic Acid Removal of Adsorbents Used in Liquid Line Filter Driers, proposed research project 1028-TRP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, April 1999 - September 2000 (ASH1028)

This research project will develop a standardized method of test to determine the capability of adsorbents to remove organic acids from circulating refrigerants and lubricants. The work will examine the influences of refrigerant and lubricant selection and demonstrate that the method is suitable both in the presence and absence of water. Organic acids can be produced in refrigeration systems that are not properly maintained or that are not functioning properly. The problem is more acute with growing use of ester lubricants. These oils are hygroscopic by nature and can be hydrolyzed to produce carboxylic acids and alcohols. Carboxylic acids, commonly referred to as organic acids, cause early system failure if allowed to remain free in

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the refrigerant system. The test solutions will include R-22 with mineral oil (MO), R-134a with a polyolester (POE), and R-410A with a POE. The adsorbents will include a 3Å molecular sieve, a 50-50 mixture of molecular sieve and alumina, alumina, and silica gel. This research project is sponsored by ASHRAE Technical Committee 3.3, *Contaminant Control in Refrigerating Systems*. Proposals are due at ASHRAE Headquarters by 18 December 1998. Further information is available from the ASHRAE Manager of Research (+1-404/636-8400).

IMPACTS

H. König (Solvay Fluor und Derivate GmbH, Germany), **Von Montreal nach Kyoto: Auswirkungen von globalen/lokalen Regulierungen von R 22, Mögliche Konsequenzen für FCKW-Ersatzstoffe** [From Montreal to Kyoto: Impacts of Global and Local Regulations of R-22, Possible Consequences for CFC Replacements*], KK Die Kälte- und Klimatechnik*, Germany, 51:, 1998 (4 pages 5 figures and 1 table in German, RDB8C04)

reviews the international regulations and projected replacements for R-22 in Germany; discusses the development of equipment and standards for refrigerants as well as alternatives for R-22; examines anticipated measures from the Kyoto Protocol; promotes use of the total equivalent warming impact (TEWI) concept in assessing refrigerant impacts; illustrations show the impacts of the Montreal Protocol on fluorochemical production, resulting bromine and chlorine concentrations in the stratosphere, use of R-22 and long-term alternatives for it in Germany, annual carbon dioxide emissions (for the USA, Germany, Russian Federation, China, and the European Union), comparative global warming potentials (GWPs) of greenhouse gases (GHGs), and the progression of infrared energy absorption by GHGs from 1990-2050

Costs and Operation

D. A. Didion (National Institute of Standards and Technology, NIST), **The Impact of Ozone-Safe Refrigerants on Refrigeration Machinery Performance and Operation**, paper 10, *Transactions* (Annual Meeting, New Orleans, LA, 17-18 November 1994), The Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1994 (15 pages with 11 figures and 5 tables, RDB4B07)

The paper summarizes requirements for a refrigerant to sustain an efficient, reliable system. It briefly outlines both the development of chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants, to fill these needs, and the concerns with ozone depletion and global warming that have arisen since. It then summarizes criteria and tradeoffs for identification of alternatives, noting that a screening of 800 industrial chemicals produced essentially no exceptions to the conclusions reached by T. Midgley in 1928. The paper outlines recent steps to commercialize equipment using alternative refrigerants, with attention to R-123 for R-11 and R-134a for R-12. The paper cites technology advances introduced to improve product efficiency, despite the lower theoretical performance of these alternatives. It notes that attention has focused on refrigerant mixtures to replace R-22 and R-502, since no single-compound refrigerants have been identified to match their thermodynamic performance. Two tables summarize the designations, compositions, maximum temperature glide at atmospheric pressure, and trade names for candidate blends containing HCFCs and those that are chlorine free. These tables list R-401A, R-401B, R-401C, R-402A, R-402B, R-403A, R-403B, R-404A, R-405A, R-406A, R-407A, R-407B, R-407C, R-408A, R-409A, R-410A, R-411A, R-411B, R-507A, R-32/125/143a (10/45/45), R-32/134a (30/70), and R-290/600a (50/50). The paper identifies advantages, concerns (e.g., composition shifting with leakage and recharging), and some circumventions for use of blends. It then addresses safety and outlines the classifications for flammability and toxicity introduced in ANSI/ASHRAE Standard 34. The paper illustrates composition shifts, with a phase diagram of R-32/134a, and the flammability shifts associated with leakage after vapor and liquid charging, for R-32/125/134a (30/10/60) and (23/25/52). The two ternary blends are developmental and commercialized versions, respectively, of R-407C. The paper outlines materials compatibility considerations, starting with stability, solubility, and lubricity of refrigerants with mineral oils. It discusses the shift from mineral oils to alkylbenzenes, polyalkylene glycols (PAGs), and polyolesters to achieve miscibility with hydrofluorocarbon (HFC) refrigerants. The paper addresses and illustrates moisture absorbance for different generic lubricant types. It then draws generalized conclusions on the compatibility of new refrigerants and lubricants with motor materials, elastomers, and engineering plastics as well as refrigerant-lubricant compatibility. It outlines efforts to identify alternatives for R-114, especially for naval uses, and discusses the prospects for R-124, R-236ea, and R-236fa. Two appendices summarize the numbering system used to identify refrigerants and the status, advantages, and limitations of R-717 (ammonia).

J. D. Douglas, **A Cost-Based Method for Comparing Alternative Refrigerants Applied to R-22 Systems,** MS thesis, Purdue University, West Lafayette, IN, December 1995 (rdb6750)

R-290, R-290/227ea, cost-based evaluation of propane and propane-blends as replacements for R-22

M. O. McLinden (National Institute of Standards and Technology, NIST), **Optimum Refrigerants for Nonideal Cycles - An Analysis Employing Corresponding States**, *Proceedings of the 1990 USNC-IIR-Purdue Refrigeration Conference and ASHRAE-Purdue CFC Conference*, edited by D. R. Tree, Purdue University, West Lafayette, IN, 69-79, July 1990 (11 pages with 7 figures, RDB0920)

The principle of corresponding states is used to evaluate the effects of the thermodynamic characteristics of working fluid performance in refrigeration cycles. Desired characteristics, expressed in terms of the critical temperature and ideal gas heat capacity using propane as the reference fluid, are examined for various departures from the theoretical (ideal) vapor-compression cycle. The baseline cycle for the comparisons include compressor efficiency and heat transfer limitations in the condenser and evaporator. The paper addresses the modified Benedict-Webb-Rubin (MBWR) equation of state chosen for property calculations, the cycle analysis simulation model, and the application of the model to the selection of alternative refrigerants. The results indicate that modifications to the basic vapor-compression cycle should be considered for refrigerants with two or more carbon atoms to achieve maximum energy efficiency.

J. Pannock and D. A. Didion (National Institute of Standards and Technology, NIST), **Performance Evaluation of Refrigerant Mixtures in Heat Pumps**, report TR-102167, Electric Power Research Institute (EPRI), Palo Alto, CA, March 1993 (250 pages with 116 figures and 4 tables, RDB3B10)

J. Pannock and D. A. Didion, **The Performance of Chlorine-Free Binary Zeotropic Refrigerant Mixtures in a Heat Pump**, report NISTIR 4748, National Institute of Standards and Technology (NIST), Gaithersburg, MD, December 1991 (78 pages with 50 figures and 2 tables, available from NTIS at price code A05, RDB2507)

This report examines zeotropic mixtures to replace R-22. 15 binary blends of R-23, R-32, R-125, R-134a, R-143a, and R-152a (all hydrofluorocarbons, HFCs) were evaluated using the CYCLE11 simulation program. The rationale for selecting these component fluids is outlined. Efficiency, volumetric capacity, suction pressures, discharge temperatures, and discharge pressures are analyzed and compared. The most promising candidates, R-32/134a and R-32/152a, were tested in a breadboard heat pump. A series of tests to evaluate use of a liquid-line heat exchanger also was performed. The findings indicate that these two zeotropes may be suitable as replacements for R-22, but that multiple tradeoffs exist in performance for different compressor speeds and mixture compositions. Performance improvements of 2 and 14% were found for R-32/152a for the low-temperature heating and high temperature cooling modes, respectively. The ozone depletion potential of this mixture is zero and the global warming potential is approximately one-fourth that of R-22, but the mixture is flammable in the entire composition range. R-32/134a mixtures, containing more than 35% R-32 by mass, yielded slightly improved performance for cooling and slightly lower for heating. Gains of 5% for cooling and 2% for low-temperature heating were measured and compared to R-22 for the equivalent speed and capacities. These results were achieved using the same test apparatus, without optimization for each fluid. Comparative efficiencies and capacities are plotted for the full range of mass fractions at selected operating conditions. An uncertainty analysis is presented in an appendix, but the test results confirm the validity of the modeling approach used.

R. Schmitz (Tecumseh Products Company), **New High Efficiency R-134a Compressor**, *Proceedings of the 45th Annual International Appliance Technical Conference* (University of Wisconsin, Madison, WI, 9-11 May 1994), IATC, Batavia, IL, 227-237, May 1994 (11 pages with 4 figures and 1 table, RDB4A27)

This paper outlines a new design for a hermetic compressor using R-134a and a polyolester (POE) lubricant. A figure shows a cutaway view of the compressor. A plot compares its efficiency with those for conventional R-12 designs in capacities of 2.4-3.4 kW (700-1000 Btu/hr), showing efficiency gains of 20-60%. The paper notes anticipation of further evolutionary improvement, to exceed a COP of 1.76 (6.0 Btu/Wh). The paper discusses the crankcase, crankshaft, bearing, and motor designs as well as changes to minimize suction and discharge plenum heat exchange, clearance volume, and re-expansion volume. Tabular data compare the operating conditions at inlet, intermediate points, and discharge for R-12 and R-134a. The paper also discusses suspension and housing

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design to reduce sound levels; a plot summarizes the results. The paper briefly cites early tests with polyalkylene glycol (PAG) lubricants and identified concerns with its hygroscopicity, partial miscibility with mineral oil used in manufacture, inadequate thermal stability, and offensive decomposition products. It mentions use of production driers and improved handling and processing to overcome the even higher hygroscopicity of POEs. Approved lubricants are identified, namely Castrol Icematic® SW-32, Henkel Emery® 2927-A, ICI Emkarate™ RL 32S, Mobil EAL Arctic® 15 and 22A, Penreco Sontex SEZ-22 and SEZ-32, and Witco Suniso® SL22 and SL32. The paper notes that viscosity and stability issues remain with POEs, but that the effects of decomposition products can be controlled with a metal passivator developed to circumvent problems, specifically blocking the function of the necessary iron catalyst. The paper briefly cites other compatibility issues, and mentions potential capillary tube plugging related to unapproved compounds in drawing condenser tubing and use of an unwanted retardant by a plastic molder. The paper notes that known technical barriers have been resolved, and that resolution of remaining lubricant and additive package issues are underway.

Environmental

D. L. Albritton (National Oceanic and Atmospheric Administration), **Ozone Depletion and Global Warming**, *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1-5, 1997 (5 pages with no figures or tables, RDB7B01)

update on the environmental impacts of refrigerant releases

N. L. Allan (University of Bristol, UK) and A. McCulloch (ICI Chemicals and Polymers Limited, UK), **Reactions of Hydrofluorocarbons and Hydrochlorofluorocarbons with the Hydroxyl Radical**, *Atmospheric Environment*, 24(9)2417-2420, 1990 (4 pages, rdb7C77)

reaction rates for hydrogen-atom abstraction by hydroxyl radicals for determination of atmospheric lifetimes hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) in the atmosphere; presents an approximate correlation between the Mulliken charge on hydrogen and the activation energy for this process; suggests that this relationship should prove useful in predictions of previously unknown rates

J. G. Anderson, D. W. Toohey, and W. H. Brune, **Free Radicals Within the Antarctic Vortex: The Role of CFCs in Antarctic Ozone Loss,** *Science*, 251:39-46, 4 January 1991 (8 pages with 6 figures, RDB1202)

This article describes experiments and observations linking chlorine and bromine concentrations with ozone depletion in the Antarctic vortex. It briefly reports the findings of the National Science Foundation Ozone Experiment (NOZE I) expedition in the austral spring of 1986. It describes in greater detail the high-altitude mission and in situ measurements of the subsequent Airborne Antarctic Ozone Experiment. Mathematical equations defining the mechanisms of ozone depletion are presented for chlorine and bromine. What sets Antarctic ozone depletion apart in the context of global change is both the severity of the phenomenon and the unusual decoupling of physical and chemical time constraints that control transformation rates in a specific region of the atmosphere. The article concludes that the dramatic reduction in ozone over the Antarctic continent would not have occurred had CFCs not been released to the atmosphere.

L. G. Anderson, **Atmospheric Chemistry of 1,1,1,2-Tetrafluoroethane,** *Atmospheric Environment*, 15(9):1579-1582, 1981 (4 pages, rdb6547)

R-134a

Atmospheric and Environmental Research, Incorporated (AER), **Estimates of the Global Warming Potential of C_3F_8**, Rhône-Poulenc Chemicals, Bristol, UK, October 1994 (14 pages with 3 figures and 5 tables, RDB5C04)

R-218, atmospheric lifetimes, radiative forcing factors, global warming potential (GWP)

J. C. Ball and T. J. Wallington, **Formation of Trifluoroacetic Acid from the Atmospheric Degradation of Hydrofluorocarbon 134a: A Human Health Concern?**, *Journal of the Air and Waste Management Association,* 43(9):1260-1262, September 1993 (3 pages, rdb65F3)

R-134a, atmospheric reactions, environmental impacts

E. P. Banks, P. N. Sharratt (University of Manchester Institute of Science and Technology, UMIST, UK), E. P. Johnson, and E. K. Clarke (Atlantic Consulting, UK), **Extending TEWI to the Production of Fluorocarbons,** *Global Warming Conference*, Austria, circa 1997 (10 pages with 1 figure and 1 table, RDB8B44)

presents a total equivalent warming impact (TEWI) analysis for production of R-227ea by a process involving R-20 (chloroform) as an intermediate and that also yields R-1114 and R-1216 through a further step involving R-22 as an intermediate; describes the production steps for R-20, R-22, R-1114, R-1216, and finally R-227ea; presents a TEWI study for R-227ea with direct (release-related) and indirect (energy-related) effects that include planned and unplanned losses as well as ultimate disposal when used as a fire suppressant; concludes that one third of the TEWI occurs in production of R-227ea

J. Barry et al., **1,1,1,3,3-Pentafluorobutane (HFC-365mfc): Atmospheric Degradation and Contribution to Radiative Forcing,** *International Journal of Chemical Kinetics*, 1997 (rdb8102)

R-365mfc, environmental impact and fate, reaction rate constant

V. D. Baxter, S. K. Fischer, and J. R. Sand (Oak Ridge National Laboratory, ORNL), **Global Warming Implications of Replacing Ozone-Depleting Refrigerants,** *ASHRAE Journal*, 40(9):23-30, September 1998 (8 pages with 7 figures, RDB9304)

summarizes the concept of total equivalent warming impact (TEWI) analysis and TEWI findings for supermarket refrigeration, heat pumps, chillers, and refrigerator-freezers (RF); concludes that carbon dioxide emissions resulting from energy use dominate the results in most of the cases examined; cites supermarket refrigeration as an exception based on the high level of refrigerant emissions; suggests that secondary loop and distributed systems hold potential to reduce TEWI in this application using either fluorocarbon or "natural" refrigerants; notes that TEWI is only one of many factors that must be considered in selecting technologies

A. C. Brown et al., *Atmospheric Environment*, 9(A):-2499-2511, 1990 (13 pages, rdb5938)

R-125 and others

J. M. Calm (Engineering Consultant), D. J. Wuebbles, and A. K. Jain (University of Illinois at Urbana-Champaign), **Impacts on Global Ozone and Climate from Use and Emission of 2,2-Dichloro-1,1,1-trifluoroethane (HCFC-123)**, *Journal of Climatic Change*, 42:439-474, June 1999 (36 pages with 10 figures and 5 tables, limited copies available from JMC as RDB9713)

This article presents a detailed study of the environmental impacts and benefits of R-123 use as a chiller refrigerant. It summarizes analyses of emissions, and consequent chlorine loading, that show that projected use of R-123 will result in a virtually indiscernible impact on stratospheric ozone. Parametric scenarios uphold this conclusion, even for extreme levels of emissions far exceeding those of current technologies and practices. Additional scenarios reaffirm the conclusion for continued use - beyond the scheduled phaseout date - as a refrigerant in closed systems. By contrast, use of this compound offers unique opportunities to reduce global warming. Moreover, time-dependent analyses show that the minimal contribution to stratospheric chlorine from R-123 emissions will not peak until more than a decade after the residual peaks of chlorine and bromine, from prior chlorofluorocarbon (CFC) and halon releases, subside. While no single index exists to compare the relative demerits of ozone depletion and climate change, three conclusions are clear. First, reversal of the buildup of bromine and chlorine (i.e., healing of the "ozone layer") is underway and progressing on target, while sufficient practical remedies for global climate change are far more difficult. Second, the analyses show that phaseout of all chlorinated, and conceptually - but much less probably - all brominated, compounds of anthropogenic origin targets some compounds that provide environmental benefits. Most chlorinated and brominated compounds do warrant phaseout; the exceptions are those with very short atmospheric lifetimes, and consequent low ozone depletion potential (ODP) that also offer offsetting environmental benefits. And third, since new global environmental concerns may, and probably will, be identified in the future, a more scientific approach is needed to determine environmental acceptability or rejection.

J. M. Calm (Engineering Consultant) and D. A. Didion (National Institute of Standards and Technology, NIST), **Trade-Offs in Refrigerant Selections: Past, Present, and Future,** *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 6-19, 1997; republished in Japanese (translation by S. Sakaida) in *Reito* [Refrigeration], Japan, 73(847):433-444 also numbered 27-38, May 1998; republished in the *International Journal of Refrigeration* (IJR), 21(4):308-321, June 1998 (14 pages with 9 figures and 8 tables, available from JMC as RDB7B02)

need for trade-offs among the several environmental, performance, and safety concerns to select refrigerants in the absence of ideal candidates: review of refrigerant history from introduction by Jacob Perkins in the 1830s, discovery of the fluorochemicals by Thomas Midgley, Jr., and his associates in 1928, to development of environmentally friendly alternatives; examines the conflict between ozone depletion, global warming, flammability, toxicity, and performance objectives from the perspective of

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chemical makeup; tabulates theoretical efficiency limits and typical efficiencies for chiller operating conditions for a range of refrigerants including R-11, R-12, R-22, R-113, R-114, R-123, R-134a, R-141b, R-236fa, R-245ca, R-245fa, R-290, R-410A, R-500, R-717, and R-744; also tabulates and presents comparative total equivalent warming impact (TEWI) findings for chiller refrigerants; examines potential replacements for R-11 and R-123 with attention to R-245fa and others; examines the impact on performance of thermodynamic properties with emphasis on temperature-entropy (TS) characteristics and their relation to liquid molar heat capacity; discusses impacts of reduced evaporating and condensing temperatures on R-410A and other refrigerants with low critical point temperatures at high efficiencies; notes that all refrigerants theoretically can achieve similar performance with cycle modifications, but that simple molecules have an inherent advantage; also notes that complex molecules need cycle modifications to overcome subcooling and other losses; demonstrates that the number of elements suitable for refrigerants is finite and that careless elimination restricts options to deal with conflicting and more serious present or future environmental concerns; illustrates the advantages of R-123, as an example, by contrasting its short atmospheric lifetime, low global warming potential (GWP), and high efficiency to very low ozone depletion potential (ODP)

J. M. Calm (Engineering Consultant), **Comparative Global Warming Impacts of Electric Vapor-Compression and Direct-Fired Absorption Equipment,** report TR-103297, Electric Power Research Institute (EPRI), Palo Alto, CA, August 1993 (82 pages with 26 figures and 10 tables, RDB4440)

This report compares the global warming impacts of electric vapor-compression and gas-fired absorption-cycle equipment for air-conditioning systems. It outlines alternatives to replace chlorofluorocarbon, and eventually also hydrochlorofluorocarbon, refrigerants. The report notes that absorption chillers do not use ozone-depleting refrigerants, but substitution of alternative refrigerants in vapor-compression equipment also offers radically-reduced or eliminated potential for stratospheric ozone depletion. Net global warming impact (or "total equivalent warming impact", TEWI), therefore, provides a better indication of environmental preferability. Examination requires consideration of both direct and indirect effects. The direct component relates to release of refrigerants that are greenhouse gases, and the indirect to carbon dioxide production in powering the equipment. The report compares the global warming potential (GWP) of common and alternative refrigerants, reviews prior studies, and presents the methodology and data used. The analyses address energy use both for chillers, at multiple efficiency levels, and associated heat rejection by cooling towers. The report then reviews historical trends and regional variations in carbon dioxide emissions for generation of electricity - the "carbon dioxide factor" (CDF). Tabular data are provided on a regional basis for the generation fuel mix, average CDF, and CDF corresponding to typical load profiles to cool commercial buildings. The generation data cover Canada, Mexico, and the United States; the regional data cover only the USA. The report presents chiller performance data, refrigerant loss data, and values used to define two scenario's used for the study. It then summarizes national and regional comparisons, reflecting generation differences. The results show that electric vapor-compression chillers consistently result in lower net warming impact than direct-fired absorption chillers. The analyses also indicate that improved performance, available at lower cost premiums than those associated with absorption chillers, offers further potential for warming reduction. Integration of thermal storage, for peak-demand reduction, offers an advantage over alternative use of gas-fired absorption-cycle chillers. Parametric analyses are presented to test the sensitivity of this finding to varied use assumptions. The report concludes with a discussion of means to reduce net warming impacts and a perspective on the occurrence of global climate change.

R. L. D. Cane and A. Morrison (Caneta Research, Incorporated, Canada), **Analysis of Alternative Refrigerants and Technology Options for Residential Heat Pumps**, *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 6, May 1999 (12 pages with 13 figures and 5 tables, RDB9839)

R-22, R-290 (propane), R-407C, R-410A

N. J. Campbell (ICI Klea) and A. McCulloch (ICI Chemicals and Polymers Limited, UK), **The Climate Change Implications of Manufacturing Refrigerants - A Calculation of 'Production Energy' Contents of Some Common Refrigerants,** *Transactions of the Institution of Chemical Engineers* (IChemE), Rugby, UK, 76(B):239-244, August 1998 (6 pages with 2 figures and 2 tables, RDB8815)

analysis of the effect of energy use in manufacturing refrigerants on total equivalent warming impact (TEWI): substances addressed include R-12, R-22, R-134a, R-600a, R-717, and cyclopentane; concludes that emissions associated with the energy to produce them is insignificant compared to later effects in their life cycles when used in refrigerators or chillers

W. K. Chang and C. S. Criddle, **Biotransformation of HCFC-22, HCFC-142b, HCFC-123, and HFC-134a by Methanotrophic Mixed Culture MM1**, *Biodegradation*, 6:1-9, 1995 (9 pages, rdb65C1)

R-22, R-123, R-134a, R-142b, environmental fate

J. Chen, V. Young, H. Nikki, and H. Magid, **Kinetic and Mechanistic Studies for Reactions of $CF_3CH_2CHF_2$ (HFC-245fa) Initiated by H-Atom Abstraction sing Atomic Chlorine**, *Journal of Physical Chemistry*, 101:2648-2653, 1997 (6 pages, rd b9404)

R-245fa, environmental impact, atmospheric chemistry

R. J. Cicerone, R. S. Stolarski, and S. Walters (University of California, Irvine, UCI), **Stratospheric Ozone Destruction by Manmade Chlorofluoromethanes**, *Science,* 185:1165-1167, 1974 (3 pages, rdb3241)

C. M. Cisson, G. A. Rausina and P. M. Stonebraker, **Human Health and Environmental Hazard Characterization of Lubricating Oil Additives**, paper 11.7, Ecological and Economical Aspects of Tribology (proceedings of the Ninth International Colloquium), Technische Academie Esslingen, Germany, 1994 (RDB6377)

lubricants, safety, environmental impacts

C. Clerbaux, R. Colin, P. C. Simon, and C. Granier, **Infrared Cross Sections and Global Warming Potentials of 10 Alternative Hydrohalocarbons**, *Journal of Geophysical Research* (JGR), 98:10491-10497, 1993 (7 pages, rdb9402)

environmental impact, fluorochemical refrigerants, GWP

J. R. Cooke and R. F. Haycock, **Lubricant Additives and the Environment**, *The Petroleum Industry Faces the Environmental Problems* (international congress), Brussels, Belgium, 1993 (rdb6378)

lubricants, safety, environmental impacts

D. L. Cooper, T. P. Cunningham (University of Liverpool, UK), N. L. Allan (University of Bristol, UK), and A. McCulloch (ICI Chemicals and Polymers Limited, UK), **Potential CFC Replacements: Tropospheric Lifetimes of C3 Hydrofluorocarbons and Hydrofluoroethers**, *Atmospheric Environment,* 27A(1):117-119, 1993 (3 pages with 2 tables, RDB-8312)

estimated lifetimes of R-E227ca1, R-E227ca2, R-227ea, R-E227ea1, R-236ca, R-E236ca1, R-236ea, R-E236ea1, R-E236ea2, R-236fa, R-245ca, R-E245ca1, R-E245ca2, R-245cb, R-E245cb1, R-E245cb2, R-245fa, R-E245fa1, R-E245fa2, R-254cb, R-E254cb1, R-E254cb2, R-254fa, R-E254fa1, R-254fb, R-E254fb1, R-E254fb2, R-263fb, R-E263fb2, R-E263fb1, R-356mff, and others: estimates are based on ab initio and semi-empirical wave functions

D. L. Cooper, T. P. Cunningham (University of Liverpool, UK), N. L. Allan (University of Bristol, UK), and A. McCulloch (ICI Chemicals and Polymers Limited, UK), **Tropospheric Lifetimes of Potential CFC Replacements: Rate Coefficients for Reaction with the Hydroxyl Radical**, *Atmospheric Environment*, 26A(7):1331-1334, 1992 (4 pages with 1 figure and 3 tables, RDB5829)

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M. F. De Flaun, B. D. Ensley, and R. J. Steffan, **Biological Oxidation of Hydrochlorofluorocarbons (HCFCs) by a Methanotrophic Bacterium**, *Bio / - Technology*, 10(12):1576-1578, 1992 (RDB65B1)

refrigerant decomposition, destruction, disposal, environmental fate

J. S. Daniel, S. Solomon, and D. L. Albritton (National Oceanic and Atmospheric Administration, NOAA), **On the Evaluation of Halocarbon Radiative Forcing and Global Warming Potentials**, *Journal of Geophysical Research* (JGR), 100(D1):1271-1285, 1995 (15 pages, rdb7C29)

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W. B. DeMore (Jet Propulsion Laboratory, JPL, California Institute of Technology), **Experimental and Estimated Rate Constants for the Reactions of Hydroxyl Radical with Several Halocarbons**, *Journal of Physical Chemistry*, 100:5813-5820, 1996 (8 pages, rdb8103)

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W. B. DeMore (Jet Propulsion Laboratory, JPL, California Institute of Technology), **Rate Constants for the Reactions of OH with HFC-134a (CF_3CH_2F) and HFC-134 (CHF_2CHF_2)**, *Kinetics and Mechanisms for the Reactions of Halogenated Organic Compounds in the Troposphere* (STEP-HALOCSIDE/AFEAS Workshop, Dublin, Ireland, 23-25 March, 1993), University of Dublin, Ireland, 1-6, 1993 (6 pages with 6 tables, RDB5844)

R-134, R-134a, environmental reactions

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W. B. DeMore (Jet Propulsion Laboratory, JPL, California Institute of Technology), **Rates of Hydroxyl Reactions with Some HFCs,** *Optical Methods in Atmospheric Chemistry* (proceedings of the SPIE), publication 1715, International Society of Optical Engineering, 72-77, 1992 (6 pages, rdb5845)

R-125, R-134, R-134a, and others; environmental reactions

B. A. Denovan and S. E. Strand, **Biological Degradation of Chlorofluorocarbons in Anaerobic Environments,** *Chemosphere*, 24(7):935-940, 1992 (6 pages, rdb7228)

refrigerant decomposition, destruction, fate

E. O. Edney and D. J. Driscoll, **Laboratory Investigations of the Deposition of Oxidation Products of Hydrochlorofluorocarbons (HCFCs) and Hydrofluorocarbons (HFCs) to Aqueous Solutions,** *Water, Air, Soil Pollution*, 66(1-2):97-110, 1993 (14 pages, rdb5952)

R-125 and others, environmental fate of refrigerants

E. O. Edney and D. J. Driscoll, **Chlorine Initiated Photo-oxidation Studies of Hydrochlorofluorocarbons (HCFCs) and Hydrofluorocarbons (HFCs): Results for HCFC-22 ($CHClF_2$), HFC-41 (CH_3F), HCFC-124 ($CClFHCF_3$), HCF-125 (CF_3CHF_2), HFC-134a (CF_3CH_2F), HCFC-142b ($CClF_2CH_3$), and HFC-152a (CHF_2CH_3)**, *International Journal of Chemical Kinetics*, 24(12):1067-1081, 1992 (15 pages, rdb5953)

R-22 ($CHClF_2$), R-41 (CH_3F), R-124 ($CHClFCF_3$), R-125 (CHF_2CF_3), R-134a (CH_2FCF_3), R-142b (CH_3CClF_2), R-152a (CH_3CHF_2), environmental fate of refrigerants

E. O. Edney, B. W. Gay, and D. J. Driscoll, **Chlorine Initiated Oxidation Studies of Hydrochlorofluorocarbons (HCFCs): Results for HCFC-123 (CF_3CHCl_2) and HCFC-141b ($CFCl_2CH_3$),** *Journal of Atmospheric Chemistry*, 12:105-120, 1991 (16 pages, rdb65C3)

R-123 ($CHCl_2F_3$), R-141b (CH_3CFCl_2), environmental fate of refrigerants

S. Fan, M. Gloor (Princeton University), J. D. Mahlman (National Oceanic and Atmospheric Administration, NOAA), S. Pacala, J. L. Sarmiento (Princeton University), T. Takahashi (Columbia University), and P. P. Tans (NOAA), **A Large Terrestrial Carbon Sink in North America Implied by Atmospheric and Oceanic Carbon Dioxide Data and Models,** *Science*, 282:442-446, 16 October 1998 (5 pages with 3 figures and 2 tables, RDB9105)

analyzes data for atmospheric carbon dioxide (CO_2) concentrations, oceanic uptake of CO_2, and emissions attributed to fossil fuel uses for 1988-1992; concludes that there is a large terrestrial uptake of CO_2 North America south of 51° northern latitude and that this continent is highly constrained, as contrasted to Eurasia and North Africa which are described as weakly constrained, and the rest of the world's land surfaces which are poorly constrained; attributes some of the North American terrestrial absorption to regrowth on abandoned farmlands and previously logged forests and to anthropogenic nitrogen deposition; examines spatial patterns and gradients in CO_2 absorption; notes an observed gradient with a decrease in CO_2 of approximately 0.3 ppm from the Pacific to Atlantic oceans [the suggested sink magnitude is approximately equal to the carbon emissions from fossil fuel use in North America, see RDB9106 for discussion]

S. J. Feldman and M. W. Spatz (AlliedSignal Incorporated), **Energy Consumption and TEWI Comparison of R-410A and HCFC-22 in a Residential Heat Pump,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 359-368, October 1995 (10 pages with 4 figures and 4 tables, available from JMC as RDB5B08)

R-22, R-410A comparison

S. B. Fels, J. D. Mahlman, M. D. Schwarzkopf, and R. D. Sinclair (National Oceanic and Atmospheric Administration, NOAA), **Stratospheric Sensitivity to Perturbations in Ozone and Carbon Dioxide,** *Journal of Atmospheric Science*, 37:2265-2297, 1980 (33 pages, rdb9107)

environmental impacts

J. Fenhann (UNEP Collaborating Centre on Energy and Environment, Denmark), **HFC, PFC and SF_6 Emission Scenarios: Recent Development in IPCC Special Report on Emission Scenarios,** *Proceedings: Joint IPCC-TEAP Expert Meeting on Options for the Limitation of Emissions of HFCs and PFCs* (26-28 May 1999), Energieonderzoek Centrum Nederland (ECN), Petten, The Netherlands, 15-33, 15 July 1999 (19 pages with 4 figures and 16 tables, RDB9602)

projects emissions of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (R-7146) through the year 2100; outlines the Intergovernmental Panel on Climate Change (IPCC) *Special Report on Emission Scenarios*; the result of calculations from the four scenarios, including other greenhouse gas (GHG) emission projections from prior assessments, indicates a range of 0.5-1.5 GtCE (giga tonne carbon equivalent, 1.1-3.3 trillion lb carbon equivalent) in the period 2010-2100; the four SRES scenarios encompass two based on economic development and two based on environmental considerations; the paper concludes that there are options to reduce GHG emissions or slow the growth in emissions even without climate policy, but that it is equally plausible that emissions will start to increase again due to increasing production activities

S. K. Fischer (Oak Ridge National Laboratory, ORNL), **Comparison of Global Warming Impacts of Automobile Air-Conditioning Concepts,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 508-515, October 1995 (8 pages, available from JMC as RDB5B20)

direct and indirect global warming, TEWI, comparison of vapor-compression using R-134a, transcritical cycle using R-744 (carbon dioxide), Stirling cycle, and thermoelectric air conditioners for mobile air conditioners (MACs)

P. Fraser (Commonwealth Scientific and Industrial Research Organization, CSIRO, Australia), D. A. Fisher (E. I. duPont de Nemours and Company, USA), P. Bloomfield (North Carolina State University, NCSU, USA), S. P. Sander (Jet Propulsion Laboratory, JPL, USA), M. K. W. Ko (Atmospheric and Environmental Research, Incorporated, AER, USA), et al., **Report on Concentrations, Lifetimes, and Trends of CFCs, Halons, and Related Species,** edited by J. A. Kaye, S. A. Penkett, and F. M. Ormond, reference publication 1339, National Aeronautics and Space Administration (NASA), Washington, DC, January 1994 (270 pages, RDB5508)

atmospheric concentrations, atmospheric lifetimes, rate constants global warming potential (GWP), production and release data

A. S. Grossman (Lawrence Livermore National Laboratory, LLNL), K. E. Grant (LLNL), W. E. Blass (University of Tennessee), and D. J. Wuebbles (University of Illinois at Urbana-Champaign), **Radiative Forcing Calculations for CH_3Cl and CH_3Br**, *Journal of Geophysical Research* (JGR), circa 1997 (2 figures and 3 tables, RDB7C28)

new estimates of the radiative forcing and global warming potentials (GWPs) for R-40 (methyl chloride) and R-40B1 (methyl bromide), two major natural (and limited anthropogenic) sources of atmospheric chlorine and bromine: results indicate that R-40 and R-40B1 have GWPs similar to that of R-50 (methane) and that current emission rates are too low to contribute to global warming at a meaningful level

S. P. Hamburg (Brown University, USA), N. Harris (European Ozone Research Coordinating Unit, UK), J. Jaeger (International Institute for Applied Systems Analysis, Austria), T. R. Karl (National Oceanic and Atmospheric Administration, NOAA, USA), M. McFarland (United Nations Environment Programme, UNEP) Ozone Secretariat, Kenya), J. F. B. Mitchell (Hadley Centre for Climate Prediction and Research, UK), M. Oppenheimer (Environmental Defense Fund, EDF, USA), B. D. Santer (Lawrence Livermore National Laboratory, LLNL, USA), S. H. Schneider (Stanford University, USA), K. E. Trenberth (National Center for Atmospheric Research, NCAR, USA), and T. M. L. Wigley (NCAR), **Common Questions about Climate Change**, United Nations Environment Program (UNEP), Nairobi, Kenya, and World Meteorological Organization (WMO), Geneva, Switzerland, undated circa 1996 (28 pages with 13 figures, available from UNEP, limited copies also available from JMC as RDB9108)

provides a simple explanation of climate and answers some of the most commonly asked questions about climate change: they include (1) has the world warmed? (2) are human activities contributing to climate change? (3) what human activities contribute to climate change? (4) how do we know that the atmospheric buildup of greenhouse gases is due to human activity? (5) what climate changes are projected? (6) how reliable are predictions of future climate? (7) are recent extreme weather events, like the large number of Atlantic hurricanes in 1995, due to global warming? (8) why do human-made greenhouse gases matter when water vapor is the most potent greenhouse gas? and (9) why should a few degrees of warming be a cause for concern?; discusses the roles of refrigerants in responses to several of these questions

G. D. Hayman, M. E. Jenkins, T. P. Murrells, and C. E. Johnson, **Tropospheric Degradation Chemistry of HCFC-123 (CF_3CHCl_2), a Proposed Replacement Fluorocarbon,** *Atmospheric Environment*, 28(3):421-437, 1994 (17 pages, rdb65C6)

R-123, lifetime, atmospheric reactions

A. E. Heathfield, C. Anastasi (University of York, UK), A. McCulloch (ICI Chemicals and Polymers Limited, UK), and F. M. Nicolaisen (University of Copenhagen, Denmark), **Integrated Infrared Absorption Coefficients of Several Partially Fluorinated Ether Compounds: CF_3OCF_2H, CF_2HOCF_2H, $CH_3OCF_2CF_2H$, CH_3OCF_2CFClH, $CH_3CH_2OCF_2CF_2H$, $CF_3CH_2OCF_2CF_2H$, and $CH_2{=}CHCH_2OCF_2CF_2H$**, *Atmospheric Environment*, 32(16):2825-2833, 1998 (9 pages with 8 figures and 4 tables, RDB8B40)

measurements of the infrared absorption coefficients at 25 °C (298 K, 77 °F) for use in calculat-

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ing global warming potentials (GWPs) for R-E125, R-E134, R-E254cb1, R-E253cb1, R-E374pcf2, R-E347mfc2, and R-E1454

A. E. Heathfield, C. Anastasi (University of York, UK), J. Ballard, D. A. Newnham (Rutherford Appleton Laboratory, UK), and A. McCulloch (ICI Chemicals and Polymers Limited, UK), **Integrated Infrared Absorption Coefficients of CF_3OCF_2H and $CH_3OCF_2CF_2H$ at 297, 253 and 213 W**, *Journal of Quantitative Spectrosc. Radiat. Transfer,* 59(1/2):91-97, 1998 (7 pages with 2 figures and 4 tables, RDB8B41)

measurements of the infrared absorption coefficients at 25, -20, and -60 °C (77, -4, and -76 °F) for use in calculating global warming potentials (GWPs) for R-E125 and R-E254cb1

A. E. Heathfield, C. Anastasi (University of York, UK), P. Pagsberg (Riso National Laboratory, Denmark), and A. McCulloch (ICI Chemicals and Polymers Limited, UK), **Atmospheric Lifetimes of Selected Fluorinated Ether Compounds**, *Atmospheric Environment, 32*(4):711-717, 1998 (7 pages with 3 figures and 5 tables, RDB8610)

rate constants and atmospheric lifetimes for R-E253cb1, R-E254cb1, R-E347mfc2, R-E374pcf2, and $CH_2{=}CHCH_2OCF_2CHF_2$

K. Hund, U. Grolms, H. King, and T. Bunemann, **Investigations of Biomass Formation During the Biodegradation of Ester-Based Lubricants**, paper 13.3, *Ecological and Economical Aspects of Tribology* (proceedings of the Ninth International Colloquium), Technische Academie Esslingen, Germany, 1994 (rdb6380)

lubricants, environmental impacts

R. Imasu, A. Suga, and T. Matsuna, **Radiative Effects and Halocarbon Global Warming Potentials of Replacement Compounds for Fluorocarbons**, *Journal of the Meteorological Society of Japan*, 73:1123-1136, 1995 (14 pages, rdb9403)

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Intergovernmental Panel on Climate Change (IPCC, of the World Meteorological Organization, WMO, and the United Nations Environment Programme, UNEP), **Climate Change 1995 - The Science of Climate Change: Summary for Policymakers and Technical Summary of the Working Group I Report**, Cambridge University Press, Cambridge, UK, 1996 (RDB6694)

overview of the Second IPCC Assessment; consensus atmospheric lifetime (τ_{atm}) and global warming potential (GWP) values

Intergovernmental Panel on Climate Change (IPCC, of the World Meteorological Organization, WMO, and the United Nations Environment Programme, UNEP), **Climate Change 1995 - Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change**, edited by J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Cambridge University Press, Cambridge, UK, 1996 (RDB6695)

detailed summary of the Second IPCC Assessment; consensus atmospheric lifetime (τ_{atm}) and global warming potential (GWP) values

Intergovernmental Panel on Climate Change (IPCC, of the World Meteorological Organization, WMO, and the United Nations Environment Programme, UNEP), **Climate Change 1995 - Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses: Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change**, edited by R. T. Watson, M. C. Zinyowera, and R. H. Moss, Cambridge University Press, Cambridge, UK, 1996 (RDB6696)

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detailed summary of the Second IPCC Assessment

Intergovernmental Panel on Climate Change (IPCC, of the World Meteorological Organization, WMO, and the United Nations Environment Programme, UNEP), **Climate Change 1994 - Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios**, edited by J. T. Houghton, L. G. Meira Filho, J. Bruce, H. Lee, B. A. Callander, E. F. Haites, N. Harris, and K. Maskell, Cambridge University Press, Cambridge, UK, 1995 (352 pages, RDB8104)

International Union of Pure and Applied Chemistry (IUPAC) Subcommittee on Gas Kinetic Data Evaluation for Atmospheric Chemistry, **Evaluated Kinetic and Photochemical Data for Atmospheric Chemistry, Supplement IV,** *Journal of Physical and Chemical Reference Data,* (6):1125-1568, 1992 (444 pages, rdb5848) alternative refrigerants, lifetime, atmospheric reactions

E. P. Johnson (Atlantic Consulting, UK), E. P. Banks, and P. N. Sharratt (University of Manchester Institute of Science and Technology, UMIST, UK), **Automobile Air Conditioning: A Case Study of CFC Replacements (Part II),** *International Journal of Life Cycle Assessment*, Germany, 3(2):75-79, 1998 (9 pages with 2 tables, RDB8B46)

presents a life cycle assessment (LCA) to compare the net global warming (GW) impact of R-134a to an R-290/600a (propane/isobutane) blend; distinguishes the method from total equivalent warming impact (TEWI) approaches by inclusion of refrigerant production implications; concludes that R-134a shows a 22-92% greater GW impact than the hydrocarbon blend, based on selected leakage and driving scenarios; notes that volatile organic compound (VOC) emissions are similar for the two options, with each slightly higher in some scenarios

E. P. Johnson, E. K. Clarke (Atlantic Consulting, UK), E. P. Banks, and P. N. Sharratt (University of Manchester Institute of Science and Technology, UMIST, UK), **Fire Extinguishers: A Case Study of CFC Replacements (Part I)**, *International Journal of Life Cycle Assessment*, Germany, 2(3):135-140, 1997 (6 pages with 1 figure and 2 tables, RDB8B45)

discusses the relevance of total equivalent warming impact (TEWI) analyses in the context of life cycle assessment (LCA); discusses allocation issues for production processes with multiple products and recovery inferences for products that are not recycled to extinction; presents a TEWI study (essentially repeated from RDB8B44) for production of R-227ea by a process involving R-20 (chloroform) as an intermediate and that also yields R-1114 and R-1216 through a further step involving R-22 as an intermediate; describes the production steps for R-20, R-22, R-1114, R-1216, and finally R-227ea; presents a TEWI study for R-227ea with direct (release-related) and indirect (energy-related) effects that include planned and unplanned losses as well as ultimate disposal when used as a fire suppressant; concludes that one third of the TEWI occurs in production of R-227ea

J. Kaiser, **Possibly Vast Greenhouse Gas Sponge Ignites Controversy**, *Science*, 282:386-387, 16 October 1998 (2 pages with 1 figure, RDB9106)

contrasts recent findings [see RDB9105] of a large carbon dioxide (CO_2) sink in North America with other findings that suggest its magnitude is smaller, that identify potential flaws or uncertainties in the data and methods, and another potential sink in tropical South America that challenges the implied balance; describes the findings of the North American sink as controversial and likely to draw criticism in the international debate on control measures for global warming; the discussion notes that some of the North American uptake may be transient based on climate changes from volcanic activity; it also notes opinions that existence of the sink is less important than changes to it

M. K. W. Ko, R-L. Shia, N-D. Sze (Atmospheric and Environmental Research, Incorporated, AER), H. Magid, and R. G. Bray (AlliedSignal Incorporated), **Atmospheric Lifetime and Global Warming Potential of HFC-245fa**, *Journal of Geophysical Research* (JGR), 104(D7):8173-8181, 1997 (9 pages with 7 figures and 4 tables, RDB9709)

R-245fa, environmental impact, GWP

M. K. W. Ko, R-L. Shia, and N-D. Sze (Atmospheric and Environmental Research, Incorporated, AER), **Calculations of Global Warming Potentials and Atmospheric Lifetimes**, report CTR97-51/P97-134, Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), Washington, DC, 1997 (16 pages with 3 figures and 7 tables, RDB8101)

estimates of the atmospheric lifetime (τ_{atm}), global warming potential (GWP), and halocarbon GWP (HGWP) for R-227ea, R-236fa, R-245ca, R-245eb, R-245fa, R-365mfc, and R-43-10meec (identified in the report as "R-43-10mee"): the GWP and HGWP for R-245eb, R-245fa, and R-43-10meec were calculated with infrared (IR) absorption cross sections and reaction rate constants specified by AFEAS; those for the remaining compounds were calculated from published sources identified by the authors (referenced in the report) and from data in the 1995 Intergovernmental Panel on Climate Change (IPCC) assessment

M. K. W. Ko, N-D. Sze (Atmospheric and Environmental Research, Incorporated, AER), and M. J. Prather (University of California, Irvine, UCI), **Better Protection of the Ozone Layer**, *Nature*, 367:505-508, 10 February 1994 (4 pages with 1 figure, RDB-9111)

proposes a strategy to limit the chlorine-bromine loading (CBL) from long-lived halocarbons and extension to the release of other ozone-depleting substances not covered by the Montreal Protocol; cited examples include rocket launches, pharmaceuticals, and fertilizers; the proposal anticipates taxes or limits based on ozone-depletion potentials (ODPs) that differentiate between the likelihood of a release reaching the stratosphere; it allows for limited use of chlorine and bromine bearing compounds considered beneficial to society for which the values and costs are to be determined by market forces or national priorities

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M. K. W. Ko, N-D. Sze, J. M. Rodriguez, D. K. Weisenstein, C. W. Heisey (Atmospheric and Environmental Research, Incorporated, AER), R. P. Wayne, P. Biggs, C. E. Canosa-Mas (University of Oxford, UK), H. W. Sidebottom, and J. Treacy (University College Dublin, Ireland), **CF_3 Chemistry: Potential Implications for Stratospheric Ozone,** *Geophysical Research Letters*, 21(2):101-104, 15 January 1994 (4 pages with 1 figure and 2 tables, RDB65B3)

> CF_3 radicals (formed by photo-degradation of R-116, R-123, R-124, R-125, R-134a, R-218, R-227ea, R-245fa, and others), atmospheric chemistry, kinetic data, estimates of ozone-depletion potentials (ODPs), uncertainties

M. K. W. Ko, N-D. Sze, G. Molnar (Atmospheric and Environmental Research, Incorporated, AER), and M. J. Prather (National Aeronautics and Space Administration, NASA), **Global Warming from Chlorofluorocarbons and Their Alternatives: Time Scales of Chemistry and Climate**, *Atmospheric Environment, 27*A(4):581-587, 1993 (7 pages with 6 figures and 2 tables, RDB6B01)

> R-10, R-11, R-12, R-22, R-113, R-114, R-115, R-140a: lifetime, radiative forcing, calculated equilibrium, resultant surface warming; results show that "for likely substitution scenarios, the warming due to halocarbons will correspond to 4-10% of the total expected greenhouse warming at the year 2100," but that uncontrolled growth of their use could result in a doubling of that effect

C. Kroeze and L. Reijnders, **Halocarbons and Global Warming**, *Science of the Total Environment*, 111(1) :1-24, 1992 (24 pages, rdb5956)

> presents a 0-dimensional computer model to calculate temperature forcing by halocarbons between 1985 and 2100; applies the model to parametric production scenarios for chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl chloroform (R-140a) and carbon tetrachloride (R-10); divides HCFCs and HFCs into two groups by their global warming potentials (GWPs), namely R-22, R-125, R-134a, R-142b, and R-143a with relatively high GWP and R-123, R-124, R-141b, and R-152a with relatively low GWP; the choice of HCFCs and restriction of HCFC and HFC applications could be the most important factors in determining the impact of halocarbons on future global warming once use of CFCs is restricted; uncontrolled use of HCFCs and HFCs from the high GWP group could increase earth's equilibrium temperature by 0.28-0.66 °C (0.50-1.19 °F) by 2100 compared to use of HCFCs and HFCs from the low GWP group; with phaseout of both CFCs and high-GWP HCFCs and HFCs by 2000 and with containment measures for low-GWP HCFCs, the long-term climatic impact of halocarbons could become lower than the present impact of halocarbons; the same holds if there is a rapid total phase-out of radiatively active halocarbons

C. Kroeze and L. Reijnders, **Halocarbons and Global Warming, II**, *Science of the Total Environment*, 112(2-3):269-290, 1992 (21 pages, rdb5957)

> investigates the impact of halons, chlorofluorocarbons (CFCs), and hydrochlorofluorocarbons (HCFCs) on global warming using an improved 0-dimensional computer model; results show that unrestricted use of HCFCs and hydrofluorocarbons (HFCs) to replace CFCs and halons may result in an equilibrium temperature increase at the earth's surface of 0.38-0.75 °C (0.68-1.35 °F) by 2100; indicates that this increase can be reduced by 40% with better housekeeping, recycling, and destruction of halocarbon wastes; phaseout of HCFCs by 2035, to protect the ozone layer, could increase temperature forcing to 0.46-1.16 °C (0.83-2.09 °F) if these HCFCs are replaced by HFCs and no emission-reducing measures are implemented; restricted use of HCFCs with containment technologies for those with low global warming potentials (GWP) and phaseout of those with high GWP could reduce global warming compared to total HCFC phaseout with HFC replacement

C. Kroeze and L. Reijnders, **Halocarbons and Global Warming, III**, *Science of the Total Environment*, 112(2-3):291-314, 1992 (24 pages, rdb5958)

> investigates the impact of halocarbon use on global warming during the next century; describes a computer model to calculate the influence on the equilibrium temperature at the earth's surface following projected applications of specific halocarbons having significant global warming potentials (GWP); projects that emissions from refrigeration and mobile air conditioning (MAC) will contribute the most to temperature forcing if hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) are used without restriction to replace chlorofluorocarbons (CFCs) and halons; projects that R-22 and R-134a will contribute the most to calculated temperature forcing; also projects that R-125, R-134a, and R-143a - mainly from refrigeration and MAC emissions - will be the most important contributors to global warming if HCFCs are phased-out to protect the ozone layer

H. J. Lamb, **How Regulation of R-23 Emissions Will Likely Impact Production of R-22**, seminar presentation charts (Winter Meeting of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, ASHRAE, Chicago, 28 January - 1 February 1995), Elf Atochem North America, Incorporated, Philadelphia, PA, 1995 (12 pages with 3 figures, available from JMC as RDB5344)

A set of charts address methods and consequences of reducing R-23 emissions in the manufacture of R-22. The introduction outlines the chemical processes to produce R-21, R-22, and R-23, by reacting R-20 (chloroform) with hydrogen fluoride (HF) in the presence of an antimony catalyst. Hydrogen chloride (HCl) is shown to be a byproduct in all three cases. The charts identify a goal of reducing greenhouse gas emissions, and R-23 in specific, as part of the October 1993 Climate Change Action Plan (CCAP). Further charts outline optimization of the reaction kinetics and identify factors to do so. An alternative option, noted as high cost, is to destroy the R-23 that results as a byproduct. The presentation notes that R-23 emissions will decrease, as R-22 production decreases and with production facility rationalization. It concludes that industry is hopeful of reducing R-23 emissions by 50% of the 1990 level by the year 2000, but that chloroform and HF availability and R-22 pricing will drive the R-22 market, rather than R-23 reduction initiatives.

P. W. Likes (Hussmann Corporation), **Supermarkets Enhance Systems to Reduce TEWI Impact**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 140-148, October 1995 (9 pages with 1 figure and 1 table, available from JMC as RDB5A54)

R-22, R-404A, R-717 (ammonia), global warming, direct and indirect effect, TEWI

J. E. Lovelock (University of Reading, UK), **Atmospheric Halocarbons and Stratospheric Ozone**, *Nature*, 252:292 ff, 1974 (rdb3522)

potential for stratospheric ozone depletion; examination of sources for chlorine and bromine

J. E. Lovelock, R. J. Maggi, and R. J. Wade (University of Reading, UK), **Halogenated Hydrocarbons and Stratospheric Ozone**, *Nature*, 241:195 ff, 19 January 1973 (rdb3523)

This landmark publication documents measurements in 1970-1972 in the northern and southern hemispheres. It notes that chlorofluorocarbons (CFCs) were found in the air and sea "wherever and whenever they were sought." [The work by Lovelock is what drew the attention of F. S. Rowland and M. J. Molina to examine the atmospheric fate of CFCs.]

J. E. Lovelock (University of Reading, UK), **Atmospheric Fluorine Compounds as Indicators of Air Movements**, *Nature*, 230:379 ff, 1971 (rdb3129)

This landmark publication documents the first known measurements of atmospheric concentrations of a chlorofluorocarbon (CFC), R-11. [The work by Lovelock is what drew the attention of F. S. Rowland and M. J. Molina to examine the atmospheric fate of CFCs.]

J. D. Mahlman (National Oceanic and Atmospheric Administration, NOAA), **Science and Nonscience Concerning Human-Caused Climate Warming,** *Annual Review of Energy and Environment*, 23:83-105, 1998 (23 pages with no figures or tables, RDB-9101)

This paper discusses the science underlying global warming with attention to the roles of climate models and climatic data. It explains and responds to the controversies surrounding global warming and offers insights on future conflicts and controversies as society begins to deal with reductions in fossil fuel uses or adaption to substantial changes in the Earth's climate. The paper outlines the history and fundamental aspect of global warming science, describes imperfections in climate models and data. It describes the context for controversy and distinguishes between misuse of information and legitimate scientific uncertainties and disagreements. It concludes with discussion of the role of assessments and the evolving controversies, indicating that they are almost guaranteed to escalate further. The paper notes that climate change raises multidimensional equity issues between winners and losers, rich and poor, environment versus economy, and the current versus future generations.

J. D. Mahlman (National Oceanic and Atmospheric Administration, NOAA), **Uncertainties in Projections of Human-Caused Climate Warming,** *Science*, 278:1416-1417, 21 November 1997 (2 pages with no figures or tables, limited copies available from JMC as RDB8B24)

policy-independent evaluation of the scientific confidence levels in predictions based on climate models of global warming and its impacts: categorizes aspects of climate change as "virtually certain facts", "virtually certain projections" (>99% confidence), "very probable projections" (>90% confidence), "probable projections" (>67% confidence), and "incorrect projections" (not supported by climate science or models); discusses the policy implications; concludes that none of the recognized uncertainties can make the problem go away and human-caused greenhouse warming will continue slowly, but inexorably, for a long time into the future; also concludes that the severity can be modest or large, depending on how remaining uncertainties are resolved and on the success in reducing emissions of long-lived greenhouse gases

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March Consulting Group (UK), **UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options**, UK Department of the Environment, Transport and the Regions (DETR), London, UK, January 1999 (RDB9132)

assesses usage and emissions of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and R-7146 (SF_6, sulfur hexafluoride) in the UK as greenhouse gases; provides information to support development of a national climate change strategy; examines the technical feasibility and cost implications of potential measures to limit future emissions; identifies 1995 UK emissions for the six gases or groups of gases controlled under the Kyoto Protocol as well as the main markets in which HFCs, PFCs, and SF_6 are used as well as additional emission sources, such as HFC emissions from R-22 production and PFC emissions from aluminum manufacturing; projects future emission for various scenarios; concludes that supermarket refrigeration, mobile air conditioning (MAC) systems, and R-23 release from R-22 manufacture will be three of the five sources collectively amounting to half of emissions of HFCs, PFCs, and SF_6 by 2010; stresses the need for a strategy to reduce emissions and examines measures to do so

March Consulting Group (UK), **Use and Emission of Selected Halocarbons: CFCs, HCFCs, HFCs, PFCs and SF_6**, UK Department of the Environment, Transport and the Regions (DETR), 1996 (available from Her Majesty's Stationery Office (HMSO), Edinburgh, UK; rdb8B37)

fluorochemical use and emissions, leakage

March Consulting Group (UK), **CFCs in the UK Refrigeration and Air Conditioning Industries - Usage and the Scope for Substitution,** UK Department of the Environment, Transport and the Regions (DETR), London, UK, 1992 (rdb8B38)

fluorochemical use and emissions, leakage

A. McCulloch (ICI Chemicals and Polymers Limited, UK) and N. J. Campbell (ICI Klea), **The Climate Change Implications of Producing Refrigerants,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 191-199, 1998 (9 pages with 2 figures and 1 table, RDB8609)

analysis of the effect of energy use in manufacturing refrigerants on total equivalent warming impact (TEWI): substances addressed include R-12, R-22, R-134a, R-600a, R-717, and cyclopentane; concludes that emissions associated with the energy to produce them is insignificant compared to later effects in their life cycles when used in refrigerators or chillers; includes discussion by M. K. Andersen (IIAR, USA) and D. Colbourne (Calor Gas Limited, UK)

A. McCulloch (ICI Chemicals and Polymers Limited, UK) and P. M. Midgley (M&D Consulting, Germany), **Estimated Historic Emissions of Fluorocarbons from the European Union,** *Atmospheric Environment*, 32(9):1571-1580, April 1998 (10 pages with 3 figures and 8 tables, RDB8B34)

sales quantities within Europe for R-11, R-12, R-22, R-113, R-114, and R-115 for 1986-1996 broken down between refrigeration, foam blowing, solvent, and aerosol uses; calculated emissions and annual emission rates for the same fluorochemicals and years; estimated sales and emissions for the same uses in 1995 and 1996 for R-22, R-123, R-124, R-134a, R-141b, and R-142b as well as calculations for 1991-1996

A. McCulloch (ICI Chemicals and Polymers Limited, UK), **Sources of Hydrochlorofluorocarbons, Hydrofluorocarbons, Fluorocarbons and Their Potential Emissions During the Next Twenty-Five Years,** *Environmental Monitoring and Assessment*, 31(1-2):167-174, 1994 (8 pages, rdb5C30)

calculates potential production and emissions of R-22, R-32, R-123, R-125, R-134a, R-141b, R-142b, and R-143a for the next 25 years based on historic data for what they replace, declared manufacturing capacities, and anticipated effects of international controls; notes that they are influenced as much by improvements to containment as by primary demands; projects that consumption of hydrochlorofluorocarbons (HCFCs) will nearly cease, but demand for R-134a could double, from approximately 150,000-300,000 t/y (165,000-331,000 ton/yr) between 1995 and 2020; demand for R-32 could rise to 90,000 t/y (99,000 ton/yr) in the same period

A. McCulloch (ICI Chemicals and Polymers Limited, UK), P. M. Midgley (M&D Consulting, Germany), and D. A. Fisher (E. I. duPont de Nemours and Company, USA), **Distribution of Emissions of Chlorofluorocarbons (CFCs) 11, 12, 113, 114 and 115 Among Reporting and Non-Reporting Countries in 1986,** *Atmospheric Environment,* 28(16):2567-2582, 1994 (16 pages with 4 figures and 6 tables, RDB5506)

R-11, R-12, R-113, R-114, R-115, production and emission data

M. McFarland (DuPont Chemicals) and J. A. Kaye (National Aeronautics and Space Administration, NASA), **Yearly Review: Chlorofluorocarbons and Ozone,** *Journal of Photochemistry and Photobiol*ogy, 55(6):911-929, 1992 (19 pages with 6 figures and 1 table, RDB6867) reviews the history of chlorofluorocarbons (CFCs) and related chemicals and current understanding their role in stratospheric ozone depletion; discusses sources of stratospheric chlorine, atmospheric concentrations, ozone photochemistry, recent developments, and alternatives to CFCs; concludes that heterogeneous chemistry in the lower stratosphere enhances ozone depletion both directly and indirectly, that responses by governments and industry are moving toward alternatives to CFCs, but that recovery of the ozone layer will not occur until the middle of the next century due to the long atmospheric lifetimes of chemicals involved; provides projections of how CFC demands might be replaced by 2000; notes that approximately 74% of future demand can be met by conservation measures and use of non-fluorocarbon alternatives, but that hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) alternatives will be required for the remaining 26%

G. Mégie (Université Pierre et Marie Curie, France), **The Scientific Interlinks Between the Montreal and Kyoto Protocols,** *Proceedings: Joint IPCC-TEAP Expert Meeting on Options for the Limitation of Emissions of HFCs and PFCs* (26-28 May 1999), Energieonderzoek Centrum Nederland (ECN), Petten, The Netherlands, 7-13, 15 July 1999 (7 pages with no figures or tables, RDB9601)

discusses the linkages between stratospheric ozone depletion and global climate change, including both positive (increasing ozone depletion and radiative forcing) and negative feedbacks; reviews the interference processes in relation to measures stipulated in the Montreal and Kyoto Protocols with emphasis on present understanding and remaining uncertainties; summarizes the effects of stratospheric ozone loss on climate change and the effects of both greenhouse gas (GHG) emissions and global warming change on ozone depletion

A. Mellouki, S. Teton, and G. LaBras, **Rate Constants for the Reaction of OH Radical with HFC-365mfc ($CH_3CH_2CF_2CH_3$)**, *Geophysical Research Letters*, 22(4):389-392, 1995 (4 pages, rdb8106)

R-365mfc, environmental impact and fate

M. S. Menzer and G. C. Hourahan (Air-Conditioning and Refrigeration Institute, ARI), **Air-Conditioning and Refrigeration's Contribution to Global Warming Gases**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 123-130, October 1995 (8 pages with 5 figures and 3 tables, corrected copy available from JMC as RDB5A01)

This paper compares the total equivalent warming impacts (TEWI) of current and older air-conditioning and refrigeration equipment. The introduction reviews the two components of TEWI, namely direct (release of refrigerant) and indirect (energy related) effects. The paper then presents the methods used to calculate TEWI by converting the direct effect to equivalent emissions of carbon dioxide. A note addresses selection of the integration time horizon (ITH) to determine the global warming potential (GWP) for this calculation. The paper discusses the dependence of TEWI on application factors, including service life, operation, refrigerant choice and associated GWP, system efficiency, and refrigerant charge and make-up rates. Typical values are tabulated for centrifugal chillers, low-temperature supermarket refrigeration systems, residential air conditioners, and domestic refrigerators. The table compares these data for equipment manufactured in 1970 and 1995. The paper briefly reviews the influences of regional generation mixes and changes on emissions; representative data are cited. Four plots then compare the direct, indirect, and total (TEWI) effects for the cited examples. A second table illustrates the sensitivity to changes in GWP and efficiency for an air conditioner. The influences are shown graphically in a plot of constant TEWI as functions of the GWP and efficiency. The paper concludes that small variations in performance have greater impact on TEWI than large variations in GWP. It cautions against dismissal of working fluids based on an arbitrary GWP threshold.

P. M. Midgley (M&D Consulting, Germany) and D. A. Fisher (E. I. duPont de Nemours and Company, USA), **The Production and Release to the Atmosphere of Halocarbon Alternatives to CFCs (HCFC-142b, HCFC-141b, and HFC-134a)**, *Atmospheric Environment*, 1997 (rdb7A41)

R-134a, R-141b, and R-142b production and emission data

P. M. Midgley (M&D Consulting, Germany) and A. McCulloch (ICI Chemicals and Polymers Limited, UK), **Estimated National Releases to the Atmosphere of Chlorodifluoromethane (HCFC-22) During 1990**, *Atmospheric Environment*, 31:809-811, 1997 (3 pages, rdb7A40)

production and emission data for R-22

M. J. Molina and F. S. Rowland (University of California, Irvine, UCI), **Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom Catalysed Destruction of Ozone**, *Nature*, 249:810-812, 1974 (3 pages with no figures or tables, RDB0928)

landmark publication that identified chlorofluorocarbons (CFCs) as sources of stratospheric

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chlorine and the resultant potential for catalyzed destruction of stratospheric ozone [This study and related work by Drs. Molina and Rowland were recognized with their receipt of the Nobel Prize in 1995.]

S. A. Montzka, J. H. Butler, R. C. Myers, T. M. Thompson, T. H. Swanson, A. D. Clarke, L. T. Lock, and J. W. Elkins, **Decline in Tropospheric Abundance of Halogens from Halocarbons: Implications for Stratospheric Ozone Depletion,** *Science*, 272:1318-1322, 1996 (5 pages, rdb7A44)

documents that ozone-depleting emissions have slowed and, in some cases stabilized or declined

C. Muller (Institut d'Aéronomie Spatiale de Belgique, Belgium), **Atmospheric Ozone and the Greenhouse Gases Observations: An Update,** *Energy Efficiency and Global Warming Impact* (proceedings of the meetings of Commissions B1 and B2, Ghent, Belgium 12-14 May 1993), International Institute of Refrigeration (IIR), Paris, France, 45-54, 1993 (8 pages with 3 figures, RDB5304)

ozone depletion, global warming, refrigerants

D. D. Nelson, M. S. Zahniser, C. E. Kolb, and H. Magid, **OH Reaction Kinetics and Atmospheric Lifetimes Estimates for several Hydrofluorocarbons,** *Journal of Physical Chemistry*, 99:16301-16306, 1995 (6 pages, rdb9401)

global warming by HFCs environmental impacts, atmospheric chemistry

J. S. Nimitz (University of New Mexico) and S. R. Skaggs (Environmental Technology and Education Consultants, ETEC), **Estimating Tropospheric Lifetimes and Ozone-Depletion Potentials of One- and Two-Carbon Hydrofluorocarbons and Hydrochlorofluorocarbons,** *Environmental Science and Technology*, 26(4):739-744, 1992 (6 pages with 4 tables, RDB5782)

estimates of the tropospheric lifetime and ozone-depletion potentials (ODP) for 53 one- and two-carbon hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs): examines relationships among carbon-hydrogen bond strength, activation energy for removal of hydrogen by the hydroxyl radical (OH), tropospheric lifetime, and ODP; presents algorithms for to estimate tropospheric lifetimes of HCFCs based on the molecular weight and composition; presented formula predicts lifetimes for molecules with atmospheric lifetimes below 30 years with a root-mean-square (rms) error of a factor of 2.4; also presents an algorithm to calculate ODPs based on the tropospheric lifetime; overall rms error of calculating ODP from the structure is cited as a factor of 2.5; provides data for R-20, R-21, R-22, R-23, R-30, R-31, R-32, R-40, R-41, R-120, R-121, R-121a, R-122, R-122a, R-122b, R-123, R-123a, R-123b, R-124, R-124a, R-125, R-130, R-130a, R-131, R-131a, R-131b, R-132, R-132a, R-132b, R-132c, R-133, R-133a, R-133b, R-134, R-134a, R-140, R-140a, R-141, R-141a, R-141b, R-142, R-142a, R-142b, R-143, R-143a, R-150, R-150a, R-151, R-151a, R-152, R-152a, R-160, and R-161

V. L. Orkin, R. E. Huie, and M. J. Kurylo (National Institute of Standards and Technology, NIST, USA), **Atmospheric Lifetimes of HFC-143a and HFC-245fa: Flash Photolysis Resonance Fluorescence Measurements of the OH Reaction Rate Constant,** *Journal of Physical Chemistry*, 100(21):8907-8912, 1996 (6 pages, rdb8107)

R-245fa and others: atmospheric lifetime, global warming potential (GWP)

V. L. Orkin (National Institute of Standards and Technology, NIST, USA), V. G. Khamaganov, A. G. Guschin (Institute of Energy Problems of Chemical Physics of the Russian Academy of Sciences, Russia), R. E. Huie, and M. J. Kurylo (NIST), **Rate Constants for the Reactions Between Hydroxyl Radicals and Fluorinated Ethers,** abstract D55, *Abstracts of the 13th International Symposium on Gas Kinetics* (11-16 September 1994), University College Dublin, Ireland, 359-360, September 1994 (2 pages with 2 tables, RDB5442)

R-125, R-E125, R-134, R-E134, R-143a, R-E143a, R-152a, R-E152a, R-245fa, R-E245fa1, atmospheric lifetime, global warming potential (GWP)

V. L. Orkin, V. G. Khamaganov, A. G. Guschin, E. E. Kasimovskaya, and I. K. Larin (Institute of Energy Problems of Chemical Physics of the Russian Academy of Sciences, Russia), **Development of Atmospheric Characteristics of Chlorine-Free Alternative Fluorocarbons,** report ORNL/Sub/86-SL103, Oak Ridge National Laboratory, Oak Ridge, TN, April 1993 (28 pages with 8 figures and 7 tables, available from JMC as RDB4890)

This report presents experimental measurements and calculations to determine global warming potential (GWP) values for R-134a and R-E143a (CH_3OCF_3). It reviews their reactions with hydroxyl radicals (OH) and outlines the experimental procedure used to measure rate constants for OH reactions. It then presents the experimental data including spectral measurements in the ultraviolet and infrared ranges. The apparatus and spectra are shown. The report concludes with discussion and tabulation of global warming potentials for integration time horizons (ITHs) of 20, 50, 100, 200, and 500 years. The data for R-134a are compared to GWP values published by others. The results for R-134a show lower GWPs than published in the *Scientific Assessment of Ozone Depletion* by the World Meteorological Organization.

S. Pinnock, M. D. Hurley, K. P. Shine, T. J. Wallington, and T. J. Smyth, **Radiative Forcing of Climate by Hydrochlorofluorocarbons and Hydrofluorocarbons,** *Journal of Geophysical Research* (JGR), 100:23227-23238, 1995 (12 pages, rdb8109)

global warming by HCFCs and HFCs, environmental impacts

M. J. Prather and C. M. Spivakovsky (National Aeronautics and Space Administration, NASA), **Tropospheric OH and the Lifetimes of Hydrochlorofluorocarbons (HCFCs),** *Journal of Geophysical Research* (JGR), 95:18,723-18,729, 1990 (7 pages, rdb7C30)

environmental impacts

M. J. Prather (University of California, Irvine, UCI, USA), P. M. Midgley (M&D Consulting, Germany), F. S. Rowland (University of California at Irvine, USA), and R. S. Stolarski (National Aeronautics and Space Administration, NASA, Goddard Space Flight Center), **The Ozone Layer: The Road Not Taken,** *Nature*, 381:551-554, 13 June 1996 (4 pages with 5 figures, RDB8B39)

examines what might have happened had use of chlorofluorocarbons (CFCs) and other ozone-depleting chemicals continued unimpeded: briefly reviews the measures to protect the stratospheric ozone layer, early stratospheric science, CFC production data, CFC buildup in the atmosphere, impacts on ozone, phaseouts under the Montreal Protocol including the 1990 London and 1992 Copenhagen amendments, and environmental consequences without the protocol; concludes that chlorine loading without the protocol would approach 9 ppb by 2010 instead of a peak 4 ppb in the 1990s; notes that ozone loss would have been 2½ times worse soon after 2000 and that the lower stratosphere might have become dominated by chlorine instead of nitrogen; also, global warming would have been accelerated since CFCs are greenhouse gases

M. J. Prather and R. T. Watson (National Aeronautics and Space Administration, NASA), **Stratospheric Ozone Depletion and Future Levels of Atmospheric Chlorine and Bromine,** *Nature*, 344:729-734, 19 April 1990 (6 pages with 6 figures and 2 tables, RDB5524)

This paper presents the influences on stratospheric chlorine concentrations of eight scenarios of regulated halocarbon emissions. It notes that atmospheric chlorine concentrations have increased from 0.6 ppb, a century ago, to 2 ppb in the late 1970s, when the ozone hole was recognized to have first occurred. It rose to more than 3 ppb by 1990, predominantly from industrial halocarbons and their photochemical byproducts. The paper suggests that predicted ozone depletion from concentrations of 3-5 ppb are modest, approximately 1-2% in the tropics and 4-6% at high latitudes. Chemical models are unable to predict the extent of changes when chlorine exceeds 5 ppb. The paper reviews the known sources of chlorine, indicating that natural sources make up only 20% and those listed in the 1987 Montreal Protocol another 50%. A table summarizes a numerical model used to calculate the atmospheric abundances of individual halocarbons. They include R-11, R-12, R-113, R-114, and R-115 as well as other compounds and hypothetical substitutes. The paper discusses uncertainties such as the timing of atmospheric response, due to the lag for air to travel from the upper troposphere to the middle stratosphere, and delays between halocarbon production and emission. It then describes and plots the impacts for eight regulatory options. They include changes in the timing, extent, substitutes, compliance, and uncertainties for phaseout of halocarbons. The paper concludes that stratospheric chlorine and bromine levels may return to those prevalent before the onset of the ozone hole, but only if more stringent regulations are applied to halocarbon production.

R. G. Prinn et al., **Atmospheric Trends and Lifetime of Trichloroethane and Global Average Hydroxyl Radical Concentrations Based on ALE-GAGE Measurements,** *Science*, 269:187-192, 1995 (6 pages, rdb8110)

atmospheric lifetime and reaction rate constant for R-140a, used to calculate the atmospheric lifetime of other species including hydrofluorocarbons (HFCs)

V. Ramaswamy, M. D. Schwarzkopf (National Oceanic and Atmospheric Administration, NOAA), and W. J. Randel (National Center for Atmospheric Research, NCAR), **Fingerprint of Ozone Depletion in the Spatial and Temporal Pattern of Recent Lower-Stratospheric Cooling,** *Nature*, 382:616-618, 15 August 1996 (3 pages with 3 figures, RDB9103)

examines a cooling trend in air temperatures in the lower stratosphere for 1979-1990 noting both spatial and seasonal variations: applies a general circulation model (GCM) to examine effects of ozone losses; notes correspondence between the latitudinal pattern of cooling in the lower stratosphere and decadal temperatures; indicates that this pattern confirms expectations that observed ozone depletion influences stratospheric cooling and that there is a small influence of other greenhouse gases; concludes that human activities, notably anthropogenic

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halocarbon emissions, influence the patterns of temperature change

V. Ramaswamy and M. M. Bowen (Princeton University), **Effect of Changes in Radiatively Active Species upon the Lower Stratospheric Temperatures,** *Journal of Geophysical Research* (JGR), 99(D9):18909-18921, 20 September 1994 (13 pages with 9 figures and 3 tables, RDB9104)

examines the thermal effects in the lower stratosphere due to changes in radiatively active chemicals; compares the influences that increase radiative forcing to those that decrease it, including both well-mixed greenhouse gases to tropospheric aerosols and stratospheric ozone loss to increases in tropospheric ozone; notes that perturbations in the concentrations of radiatively active species leads to temperature decrease in the lower stratosphere; indicates that tropospheric ozone increases enhance lower stratospheric cooling beyond that caused by stratospheric ozone depletion

V. Ramaswamy (Princeton University), M. D. Schwarzkopf, and K. P. Shine (National Oceanic and Atmospheric Administration, NOAA), **Radiative Forcing of Climate from Halocarbon-Induced Global Stratospheric Ozone Loss**, *Nature,* 355:810-812, 27 February 1992 (3 pages with 1 figure and 1 table, RDB7A33)

discusses interactions between stratospheric ozone depletion and global warming with specific attention to the diminished radiative forcing from stratospheric ozone, a natural greenhouse gas, due to halocarbon emissions: notes that data from satellite and ground-based instruments indicate that a reduced ozone level in the lower stratosphere for the middle to high latitudes in both hemispheres between 1979 and 1990; examines the radiative forcing of the surface-troposphere system from these ozone losses; compares it with that due to the increased concentrations of the other main radiatively active gases (carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons) over the same time period; indicates that significant negative radiative forcing results from ozone losses in middle to high latitudes; also indicates that the negative radiative forcing was caused by the CFCs and other gases; concludes that the net decadal contribution of CFCs to the greenhouse climate forcing is substantially less than previously estimated since the anthropogenic emissions of CFCs and other halocarbons are largely responsible for the observed ozone depletion

A. R. Ravishankara, A. A. Turnipseed, N. R. Jensen, S. Barone, M. Mills, C. J. Howard, and S. Solomon (National Oceanic and Atmospheric Administration), **Do Hydrofluorocarbons Destroy Stratospheric Ozone**, *Science*, 263:71-75, 1994 (5 pages, rdb7A42)

HFCs, ozone depletion, ODP

D. T. Reindl, D. E. Knebel, and R. A. Gansler (Thermal Storage Applications Research Center, TSARC, University of Wisconsin), **Characterizing the Marginal Basis Source Energy and Emissions Associated with Comfort Cooling Systems,** paper CH-95-22-4, *Transactions* (Winter Meeting, Chicago, IL, 28 January - 1 February 1995), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 101(1):-1353-1363, 1995 (11 pages with 12 figures and 5 tables, RDB5262)

J. M. Rodriguez, M. K. W. Ko, N-D. Sze, and C. W. Heisey (Atmospheric and Environmental Research, Incorporated, AER), **Two-Dimensional Assessment of the Degradation of HFC-134a: Tropospheric Accumulations and Deposition of Trifluoroacetic Acid**, *Kinetics and Mechanisms for the Reactions of Halogenated Organic Compounds in the Troposphere* (proceedings of the STEP-HALOCSIDE/AFEAS Workshop, Dublin, Ireland, 23-25 March 1993), 104-112, 1993 (9 pages, RDB-65D7)

R-134a, atmospheric chemistry

C. M. Roehl, D. Boglu, C. Brühl, and G. K. Moortgat (Max-Planck-Institut für Chemie, Germany), **Infrared Ban Intensities and Global Warming Potentials of CF_4, C_2F_6, C_3F_8, C_4F_{10}, C_5F_{12}, and C_6F_{14}**, *Geophysical Research Letters,* 22(7):815-818, 1 April 1995 (4 pages with 4 tables, RDB5C05)

R-14, R-116, R-218, R-31-10, R-41-12, R-51-14, GWP

F. S. Rowland (University of California, Irvine, UCI), **The CFC Controversy: Issues and Answers**, *ASHRAE Journal,* 34(12):20-27, December 1992 (6 pages with 4 tables, RDB3223)

F. S. Rowland (University of California, Irvine, UCI), **Stratospheric Ozone Depletion by Chlorofluorocarbons**, *Ambio,* 19(6-7):281-292, 1990 (12 pages, rdb6550)

CFCs and alternative refrigerants

F. S. Rowland and M. J. Molina (University of California, Irvine, UCI), **Chlorofluoromethanes in the Environment**, *Reviews of Geophysics and Space Physics,* 13(12):1191-1192, 1975 (2 pages, rdb0927)

R-11, R-12, and others, environmental impacts

J. R. Sand, S. K. Fischer, and V. D. Baxter (Oak Ridge National Laboratory, ORNL), **Energy and**

Global Warming Impacts of HFC Refrigerants and Emerging Technologies, Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) and U.S. Department of Energy (DOE), Washington, DC, 1997 (222 pages with 53 figures and 65 tables, limited copies available from JMC as RDB7C04)

summarizes results from the third phase of a study to compare the global warming impacts of alternative technologies for air conditioning, refrigeration, and appliance insulation; focuses on refrigerants and insulation blowing agents to replace those being phased out under the Montreal Protocol; analyses use a systems approach to determine the total equivalent global warming impact (TEWI) for refrigerants and blowing agents with zero ozone depletion potential (ODP), existing not-in-kind (NIK) technologies, and NIK technologies not yet commercialized; assesses the impacts of R-22, R-134a, R-141b, R-152a, R-236ea, R-245ca, R-245fa, R-290 (propane), R-356mff ("R-356mffm"), R-365mfc, R-404A, R-407C, R-410A, R-502, 507A, R-717 (ammonia), R-744 (carbon dioxide), R-22/142b, cyclopentane, other hydrocarbons, engine-driven systems, absorption-cycle chillers and heat pumps, desiccant dehumidification, advanced vapor-compression systems, and evacuated panel insulation; covers refrigerator freezers, unitary air-conditioning equipment, supermarket refrigeration systems, chillers, and automobile air conditioners; notes that TEWI is not the only criterion that must be considered, but that safety, costs, local factors, reliability, and other considerations also apply; concludes that energy efficiency and reduced refrigerant emissions are the most effective means to mitigate future anthropogenic contributions to climate change

J. R. Sand, S. K. Fischer, and V. D. Baxter (Oak Ridge National Laboratory, ORNL), **Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies - Executive Summary**, Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) and U.S. Department of Energy (DOE), Washington, DC, 1997 (28 pages with 11 figures and 2 tables, RDB7C05)

summarizes results study [see RDB7C04] to compare the global warming impacts of alternative technologies for air conditioning, refrigeration, and appliance insulation; focuses on refrigerants and insulation blowing agents to replace those being phased out under the Montreal Protocol; analyses use a systems approach to determine the total equivalent global warming impact (TEWI) for refrigerants and blowing agents with zero ozone depletion potential (ODP), existing not-in-kind (NIK) technologies, and NIK technologies not yet commercialized; notes that TEWI is not the only criterion that must be considered, but that safety, costs, local factors, reliability, and other considerations also apply; concludes that energy efficiency and reduced refrigerant emissions are the most effective means to mitigate future anthropogenic contributions to climate change

A. M. Schmoltner, R. K. Talukdar, R. F. Warren, A. Mellouki, L. Goldfarb, T. Gierczak, S. A. McKeen, and A. R. Ravishankara, **Rate Constants for Reactions of Several Hydrofluorocarbons with OH and $O(^1D)$ and Their Atmospheric Lifetimes**, *Journal of Physical Chemistry,* 97(35):8976-8982, 1993 (7 pages, rdb5C32)

R-32 and others, atmospheric reactions

S. E. Schwarzkopf (U.S. Fish and Wildlife Service), **CFC Alternatives Under a Cloud**, *Nature,* 376:297-298, 27 July 1995 (2 pages with 2 figures, RDB7A48)

questions whether local concentrations of trifluoroacetic acid (TFA) could build to unacceptable levels, particularly in water bodies characterized by little or no outflow and high evaporation rates; suggests that enhancement of solute concentrations in shallow groundwater in arid regions also could lead to high local concentrations; notes that TFA is resistant to abiotic degradation processes such as photolysis and hydrolysis and also that it is virtually unmetabolizable by most plants and animals; acknowledges that hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) are necessary as alternatives to replace chlorofluorocarbons (CFCs), but notes that TFA is likely to be an extremely persistent compound that may not be universally benign when alternative fluorochemicals are released in kilotonne quantities

A. Sekiya and M. Tamura (National Institute of Materials and Chemical Research, NIMC, Japan), **Infrared Absorption of Fluorocarbons Related to the Greenhouse Warming Potential,** *Kagaku Gijutsu Kenkyusho Hokoku,* Japan, 85(7):245-249, 1990 (6 pages with 5 tables, in Japanese with English abstract and tables, RDB5964)

relative infrared (IR) absorption by weight and by mole of R-11, R-12, R-13, R-14, R-21, R-22, R-32, R-41, R-113, R-113a, R-114, R-115, R-116, R-121, R-122, R-123, R-123a, R-125, R-131, R-131a, R-132b, R-134, R-141, R-141b, R-142b, R-143, R-143a, R-152a, R-161, R-217ba, R-218, R-225da, R-236ea, R-261ba, and R-744; IR absorption and hydrocarbon global warming potential (HGWP) of R-11, R-12, R-22, R-113, R-22, R-123, R-125, R-141b, R-142b, R-143a, and R-152a

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H. W. Sibley (Carrier Corporation), **An Environmental Assessment of Performance Trends in Air Conditioners and Heat Pumps,** *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 131-139, October 1995 (9 pages with 4 figures and 2 tables, available from JMC as RDB5A53)

global warming, direct and indirect effect, TEWI, efficiency and emission trends

H. W. Sidebottom (University College Dublin, Ireland) and J. Franklin (Alternative Fluorocarbons Environmental Acceptability Study, AFEAS, USA), **The Atmospheric Fate and Impact of Hydrochlorofluorocarbons and Chlorinated Solvents**, *Pure and Applied Chemistry*, 68(9):1757-1769, 1996 (13 pages with 6 figures and 1 table, RDB7754)

examines the atmospheric behavior of hydrochlorofluorocarbons (HCFCs) and chlorinated solvents, described as two classes of volatile chlorinated aliphatic compounds used on a large scale with considerable societal benefits: paper addresses R-22, R-123, R-124, R-141b, and R-142b in the HCFC group and R-30, R-140a (methyl chloroform), R-1110, and R-1120 in the solvent group; concludes that with the exception of R-140a (methyl chloroform), these compounds make only a small or insignificant contribution to stratospheric ozone depletion, global warming, photo-chemical smog, acid rain, or chloride or fluoride levels in precipitation; identifies the atmospheric degradation paths and products for the cited compounds

P. G. Simmonds, R. G. Derwent, A. McCulloch, S. O'Dougherty, and A. Gaudry, **Long-Term Trends in Concentrations of Halocarbons and Radiatively Active Trace Gases in Atlantic and European Air Masses Monitored at Mace Head, Ireland, from 1987-1994**, *Atmospheric Environment,* 30(23):-4041-4063, 1996 (23 pages, rdb7A45)

documents that ozone-depleting emissions have slowed and, in some cases stabilized or declined

S. Solomon, J. B. Burkholder, A. R. Ravishankara, and R. R. Garcia, **Ozone Depletion and Global Warming Potentials of CF_3I**, *Journal of Geophysical Research* (JGR), 99(D10):20929-20935, October 1994 (7 pages, rdb5A23)

R-13I1, ODP, GWP

S. Solomon and D. L. Albritton (National Oceanic and Atmospheric Administration), **Time-Dependent Ozone Depletion Potentials for Short- and Long-Term Forecasts**, *Nature*, 357:33-37, 7 May 1992 (5 pages with 3 figures and 2 tables, RDB-2A15)

ODP

S. Solomon, M. Mills (National Oceanic and Atmospheric Administration), L. E. Heidt, W. H. Pollock (National Center for Atmospheric Research), and A. F. Tuck (National Oceanic and Atmospheric Administration), **On the Evaluation of Ozone Depletion Potentials**, *Journal of Geophysical Research* (JGR), 97(D1):825-842, 20 January 1992 (18 pages with 12 figures and 5 tables, RDB2A16)

ODP

R. S. Stolarski and R. J. Cicerone (University of California, Irvine, UCI), **Stratospheric Chlorine: A Possible Sink for Ozone,** *Canadian Journal of Chemistry*, 52:1610-1615, 1974 (6 pages, rdb3240)

R. Talukdar, A. Mellouki, T. Gierczak, J. B. Burkholder, S. A. McKeen, and A. R. Ravishankara, **Atmospheric Fate of Difluoromethane, 1,1,1-Trifluoroethane, Pentafluoroethane, and 1,1-Dichloro-1-fluoroethane: Rate Coefficients for Reactions with Hydroxyl and UV Absorption Cross Sections of 1,1-Dichloro-1-fluoroethane**, *Journal of Physical Chemistry*, 95(15):5815-5821, 1991 (7 pages, rdb5835)

R-32, R-125, R-141b, R-143a, atmospheric reactions

M. L. Tosato et al., **Multivariate Modeling of the Rate Constant of the Gas-Phase Reaction of Haloalkanes with the Hydroxyl Radical**, *Science of the Total Environment*, 109-110:307-325, 1991 (19 pages, rdb5840)

atmospheric reactions

T. K. Tromp, M. K. W. Ko, J. M. Rodriguez, and N-D. Sze (Atmospheric and Environmental Research, Incorporated, AER), **Potential Accumulation of a CFC-Replacement Degradation Product in Seasonal Wetlands**, *Nature*, 376:327-330, 27 July 1995 (4 pages with 3 figures, RDB7A49)

analysis shows that trifluoroacetate (TFA) concentrations could become appreciable, within several decades, in the local surface waters of seasonal wetlands for conditions of high evapotranspiration where removal by degradation and seepage is limited: observes that TFA will not have any biological effects in wetlands if its concentration is limited to the projected global average rainwater concentration, but that enhanced concentrations may be concerns for some conditions [This analysis incorporated emission projections provided by the U.S. Environmental Protection Agency (EPA) for R-123, R-124, and R-134a; the R-123 release data are much higher than those from other sources. These data would accelerate the effect discussed, but not change the ultimate conclusions.]

E. C. Tuazon and R. Atkinson (University of California at Riverside), **Tropospheric Degradation Products of Hydrochlorofluorocarbons and Hydrofluorocarbons. Potential Replacements for the Chlorofluorocarbons and Halons,** *Halon Replacements, Technology and Science* (208th National Meeting, Washington, DC, 21-25 August 1994), ACS Symposium Series 611, American Chemical Society (ACS), Washington, DC, 41-49, 1995 (9 pages, rdb6308)

R-141b, R-142b, and others, environmental impacts, atmospheric reactions

E. C. Tuazon and R. Atkinson (University of California at Riverside), **Tropospheric Transformation Products of a Series of Hydrofluorocarbons and Hydrochlorofluorocarbons**, *Journal of Atmospheric Chemistry*, 17(2):179-199, 1993 (21 pages, rdb5965)

R-123, R-125, and others, atmospheric reactions

E. C. Tuazon et al., **Rate Constants for the Gas-Phase Reactions of Chlorine Atoms with a Series of Hydrofluorocarbons and Hydrochlorofluorocarbons at 298 ± 2 K** [25 °C, 77 °F], *International Journal of Chemical Kinetics*, 24(10):917 ff, 1992 (rdb5966)

R-125 and others, atmospheric reactions, lifetime

E. C. Tuazon et al., **Rate Constants for the Gas-Phase Reactions of Chlorine Atoms with a Series of Hydrofluorocarbons and Hydrochlorofluorocarbons at 298 ± 2 K** [25 °C, 77 °F], *International Journal of Chemical Kinetics*, 24(7):639-648, 1992 (10 pages, rdb6459)

R-125 and others, atmospheric reactions, lifetime

Z. Ure (ACDP Consulting Engineers, UK), **Effective Control, Energy Efficiency and System Diversification Influence on TEWI**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:1021-1028, 1995 (8 pages with 7 figures and 1 table, RDB7939)

influence of energy-related (indirect effect) emission on total equivalent warming impact (TEWI): discussion of direct (refrigerant emission) and indirect effects, carbon dioxide releases per kWh electricity generated by country, and effect of load profiles and time-of-day load shifting; effects of storage and use of absorption systems for peak demand reduction; comparative efficiencies of a compressor for R-12, R-22, R-134a, R-290 (propane), R-502, and R-717 (ammonia) for air conditioning and refrigeration

UK Stratospheric Ozone Review Group, **Stratospheric Ozone: 1996**, Her Majesty's Stationery Office (HMSO), Edinburgh, UK, 1996 (rdb7A43)

calculated and projected impacts on stratospheric ozone from natural and anthropogenic chemicals

F. A. Vogelsberg, **Stratospheric Ozone Depletion and Linkage to Climate Change**, unpublished seminar presentation charts (Winter Meeting of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, ASHRAE, Chicago, 28 January - 1 February 1995), DuPont Chemicals, Wilmington, DE, February 1995 (20 pages with 3 figures, available from JMC as RDB5348)

This series of 19 presentation charts provides an update on the understanding of stratospheric ozone depletion, global warming, and their linkage. The summary of ozone depletion draws on the "*Scientific Assessment of Ozone Depletion: 1994*" by NOAA, NASA, UNEP, and WMO [see RDB5301 and RDB5302]. It addresses confirmation of ozone loss, the current and projected extents of that phenomenon, relationship to man-made emissions, consequences of hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) use, and implications for policy making. A plots shows the cumulative equivalent chlorine loading of natural and anthropogenic chemicals for 1979-2054. Another depicts the global consumption of chlorofluorocarbons (CFCs) for 1986-1992. It reveals that consumption outside the developed countries is projected to exceed that in developed countries in 1994. A third figure shows global consumption of CFC refrigerants by major countries or groups of countries. The charts then outline key issues anticipated to surface in the next meeting of Parties to the Montreal Protocol. The update on global warming capsulizes the "*1994 Report of the Scientific Assessment Working Group*" of the IPCC [see RDB4B13]. A series of charts indicates the levels of scientific confidence in climate change and resultant impacts. Two final charts introduce and summarize an investigation by Oak Ridge National Laboratory (ORNL) of total equivalent warming impacts [see RDB5509].

D. Hartmann (University of Washington), S. Vogel (science writer), and L. Farrow (National Oceanic and Atmospheric Administration, NOAA), **Reports to the Nation on our Changing Planet: Our Changing Climate**, report 4, University Corporation for Atmospheric Research (UCAR) Joint Office for Science Support, fall 1997 (28 pages with 10 figures, RDB9109)

explains in simple terms the effects that have and are changing the climate, both natural and

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of human origin (anthropogenic): explains the dynamic climate system, factors that may change it, the greenhouse effect, changes in greenhouse gases including refrigerants, and the role of aerosols with emphasis on sulfate aerosols and the sunscreen effect; discusses climate changes in the past century, prediction of climate change, use of models to predict future changes, and directions for the future

T. J. Wallington, W. F. Schneider (Ford Research Laboratory, USA), O. J. Nielsen, J. Sehested (Risø National Laboratory, Denmark), D. R. Wornsop (Aerodyne Research, Incorporated, USA), W. J. DeBruyn, and J. A. Shorter (Boston College, USA), **Atmospheric Chemistry and Environmental Impact of Hydrofluorocarbons and Hydrochlorofluorocarbons**, *Halon Replacements, Technology and Science* (208th National Meeting, Washington, DC, 21-25 August 1994), ACS Symposium Series 611, American Chemical Society (ACS), Washington, DC, chapter 3, 16-30, 1995 (15 pages with 2 figures and 3 tables, RDB6307)

atmospheric chemistry and environmental impacts of HCFCs and HFCs including R-22, R-23, R-32, R-123, R-124, R-125, R-134a, R-141b, R-142b, and R-143a with comparisons to R-11, R-12, and R-744 (carbon dioxide); atmospheric lifetimes, ozone depletion potential (ODP), halocarbon global warming potential (HGWP), gas- and aqueous-phase atmospheric degradation products, heterogeneous and aqueous phase chemistry, formation of toxic or noxious products including trifluoroacetic acid (TFA, CF_3CO_2H) in rainwater

T. J. Wallington, W. F. Schneider (Ford Research Laboratory), D. R. Worsnop (Aerodyne Research, Incorporated, USA), O. J. Nielsen, J. Sehested (Risø National Laboratory, Denmark), W. J. DeBruyn, and J. A. Shorter (Boston College, USA), **The Environmental Impact of CFC Replacements - HFCs and HCFCs**, *Environmental Science and Technology*, 28(7):320A-326A, 1994 (7 pages, rdb5C34)

environmental impacts

W. C. Wang (University of Science, Malaysia), **Climatic Effects Due to Increasing Atmospheric Trace Gases and their Induced Ozone Changes**, *Ozone Depletion: Implications For The Tropics* (proceedings of the International Conference on Tropical Ozone and Atmospheric Change, Penang, Malaysia, 20-23 February 1990), edited by M. Ilyas, United Nations Environment Programme (UNEP), Nairobi, Kenya, 292-301, 1991 (10 pages, RDB-7C76)

ozone depleting effects from releases of R-11, R-12, R-22, R-113, R-115, R-123, R-124, R-141b, R-142b, and others; environmental impacts

O. Wild, O. V. Rattigan, R. L. Jones, J. A. Pyle, and R. A. Cox (University of Cambridge, UK), **Two-Dimensional Modelling of Some CFC Replacement Compounds**, *Journal of Atmospheric Chemistry*, 25:167-199, 1996 (33 pages, rdb7755)

examines the atmospheric distributions, lifetimes, and degradation products of R-123, R-134a, R-141b, R-142b, and R-152a; concludes that R-123 and R-152a are removed relatively rapidly in the troposphere by reaction with hydroxyl radicals; also concludes that R-141b has the greatest potential of the five compounds to increase chlorine loading in the lower stratosphere

M. A. Wright, **Biodegradation of ICI Synthetic Lubricants**, PhD thesis, Cranfield Institute of Technology, UK, 1993 (rdb6384)

lubricants, environmental impacts

D. J. Wuebbles (University of Illinois at Urbana-Champaign) and J. M. Calm (Engineering Consultant), **An Environmental Rationale for Retention of Endangered Chemicals**, *Science*, 278:1090-1091, 7 November 1997 (2 pages with 2 figures, limited copies available from JMC as RDB7C01)

This article outlines analyses of R-123 as an example of a chemical that is being phased out under the Montreal Protocol based on chlorine content, but which offers important and offsetting environmental benefits. The dominant use of R-123 is in centrifugal chillers. The analyses show that R-123's low ozone depletion potential (ODP) of 0.014 coupled with time-based emissions yield an inconsequential impact on chlorine-bromine loading (CBL). The CBL impact is shown to be 0.002% of the total and 0.007% for a combination of worst-case projections, but much lower at the time of the CBL peak from other anthropogenic emissions. In contrast, R-123's short atmospheric lifetime (τ_{atm}) of 1.4 years and low global warming potential (GWP) for 100-year integration of 90 are very favorable. Combined with thermodynamic efficiency that is 3-5% higher than alternatives and 9-20% higher in current equipment, R-123 use offers an important means to reduce greenhouse gas omissions. The paper notes that there is no single measure to compare ozone depletion and global warming effects, but the negligible impact on CBL does not justify discarding an important option to address global warming. The article cites other chemicals slated for phaseout that also may have indiscernible ozone impacts, among them R-13B1 (halon 1000), R-124, and R-280faB1 (halon 3001). It speculates that R-123 probably would have survived phase out had the global warming regulations been implemented before those for ozone depletion. The article concludes that use of single measure

ODP controls places excessive emphasis on the process rather than the objectives, that containment and recovery would suffice to address beneficial chemicals with short τ_{atm}, and that associated energy use must be considered along with GWP in assessing the impacts of global warming concerns. The article also notes that careless elimination of options can be more harmful than beneficial for compounds with short τ_{atm} and the potential for energy savings.

D. J. Wuebbles, A. K. Jain, and Z. Li, **The Atmospheric Lifetime and Estimated Global Warming Potentials for Perfluoropropylene (C_3F_6),** University of Illinois at Urbana-Champaign, Urbana, IL, 1997 (3 pages with no figures or tables, RDB7C31)

τ_{atm} and GWP for R-1216

D. J. Wuebbles, Z. Li, and K. O. Patten, **Estimated Ozone Depletion Potentials and Global Warming Potentials for 1-C_3F_7I, 1-C_4F_9I, and 1-$C_6F_{13}I$**, University of Illinois at Urbana-Champaign, Urbana, IL, 1997 (9 pages with 2 figures, RDB7C32)

atmospheric lifetimes (τ_{atm}), ODP, and GWP for the perfluoroalkyl iodides R-217cal1, R-319mccl1, and R-51-13mccccl1

D. J. Wuebbles (University of Illinois at Urbana-Champaign) and D. E. Kinnison (Lawrence Livermore National Laboratory, LLNL), **Predictions of Future Ozone Changes**, *International Journal of Environmental Studies,* 51:269-283, 1996 (15 pages with 4 figures, RDB7207)

numerical models of global atmospheric chemistry, Chlorine/Bromine Loading, equivalent stratospheric chlorine predictions based on assumed compliance with the Copenhagen Amendments to the Montreal Protocol, changes in stratospheric ozone from chlorofluorocarbons (CFCs) and other halocarbons

D. J. Wuebbles (University of Illinois at Urbana-Champaign), **Three-Dimensional Chemistry in the Greenhouse**, *Journal of Climatic Change,* 34:397-404, 1996 (8 pages with no figures or tables, RDB7208)

editorial comment on atmospheric modeling of chemical processes in the troposphere and stratosphere; evolution from simplified weighing functions, such as the Global Warming Potential (GWP), to one- (1-D), two- (2-D), and three-dimensional (3-D) models; comparative computational burdens; application and limitations of chemical models for climate studies; complexity of tropospheric processes and consequent, interim reliance on 2-D models

D. J. Wuebbles (University of Illinois at Urbana-Champaign), **Weighing Functions for Ozone Depletion and Greenhouse Gas Effects on Climate**, *Annual Review of Energy and Environment,* 20:45-70, 1995 (26 pages with 4 figures and 6 tables, RDB7209)

indices for environmental concerns from chemical releases; atmospheric concentrations and lifetimes; model-calculated and semiempirical approaches for ozone depletion potential (ODP); time-dependent effects; relative radiative forcing, global warming potential (GWP) and dependence on the integration time horizon, absolute global warming potential (AGWP) to avoid the reference basis, and other GWP formulations; direct and indirect GWPs; limitations on use of ODP and GWP indices; tabular data for R-11, R-12, R-12B1, R-13B1, R-13I1, R-14, R-22, R-23, R-32, R-40B1 (methyl bromide), R-50 (methane), R-113, R-116, R-123, R-124, R-125, R-134a, R-140a (methyl chloroform), R-141b, R-143a, R-152a, R-744 (carbon dioxide), R-744A (nitrous oxide), and R-7146

D. J. Wuebbles (Lawrence Livermore National Laboratory, LLNL), **The Role of Refrigerants in Climate Change**, *International Journal of Refrigeration* (IJR), 17(1):7-17, January 1994 (11 pages with 9 figures and 3 tables, RDB7B17)

reviews the role of refrigerants in affecting climate with attention to ozone depletion and global warming: summarizes the basic mechanisms of global warming and tabulates the relative radiative forcing effects of R-11, R-12, R-22, R-114, R-115, R-123, R-124, R-134a, R-141b, and R-152a; discusses the atmospheric concentrations and trends for these fluorochemicals (due to emissions from refrigerant and other uses); discusses the potential response of climate including surface temperatures, feedback effects, and significance of climate change; tabulates the global warming potentials (GWPs) for the cited refrigerants and discusses policy analyses; paper concludes that the increased radiative forcing (warming effect) of atmospheric concentrations of chlorofluorocarbons (CFCs) and related halocarbons is comparable in magnitude to the offsetting negative forcing (cooling effect) from stratospheric ozone loss due to these chemicals; the replacements will have a smaller warming effect, but there should be less cancellation for these ozone-friendly compounds

D. J. Wuebbles (Lawrence Livermore National Laboratory, LLNL) and J. Edmonds, **Primer on Greenhouse Gases**, Lewis Publishers, Chelsea, MI, USA, 1991 (230 pages, rdb3972)

global warming, greenhouse gases, environmental impact

please see page 6 for ordering information

D. J. Wuebbles (Lawrence Livermore National Laboratory, LLNL), **Chlorofluorocarbon Emission Scenarios: Potential Impact on Stratospheric Ozone**, paper 2C1676, *Journal of Geophysical Research* (JGR), 88(C2):1433-1443, 1983 (11 pages with 13 figures and 5 tables, RDB5523)

This paper summarizes theoretical analyses of the influence of chlorocarbon emissions on the atmosphere and to stratospheric ozone depletion in particular. Prior analyses focused on R-11 and R-12. The new results indicate that R-10 (carbon tetrachloride), R-113, and R-140a (methyl chloroform) also could contribute significantly. The paper briefly reviews the scientific understanding of ozone depletion and the evolution of model calculations. It then outlines 15 scenarios developed by the Organization for Economic Cooperation and Development (OECD), and three added cases, to assess potential growth and decline in chlorocarbon releases. The calculated changes in total column ozone are tabulated for 1950-2100 for the 18 scenarios. Steady state projections are included for scenarios reflecting constant emissions following 1980 and the same with increased R-10 emissions. Plots summarize the changes in total ozone with time for the 18 scenarios. A table summarizes the relative efficiencies of halocarbons for the no-growth scenario, noting that R-11 and R-12 account for approximately 70% of the ozone loss at steady state conditions. A figure shows the changes in local ozone concentrations by altitude, at selected times, for the no-growth scenario. Two others depict variants with increases and decreases of 7% per year in chlorocarbon emissions after January 2000. The paper concludes with discussion of changes in surface temperature from increased concentrations of R-11 and R-12, by their actions as greenhouse gases. An appendix describes the LLNL Transport-Kinetics Model used.

D. J. Wuebbles, F. M. Luther, and J. E. Penner (Lawrence Livermore National Laboratory, LLNL), **Effect of Coupled Anthropogenic Perturbations on Stratospheric Ozone**, paper 2C1675, *Journal of Geophysical Research* (JGR), 88(C2):1444-1456, 1983 (13 pages, RDB5510)

This paper discusses the interactions of anthropogenic influences on stratospheric ozone. Chlorocarbon, carbon dioxide, nitrous oxide, and NO_x emissions are identified as coupled perturbations. The paper summarizes calculations of changes due to chlorocarbon emissions, how the other perturbations may have influenced the actual change in ozone, and how both may influence future changes in ozone. It concludes that increasing CO_2 concentrations will have a large offsetting influence to ozone losses from chlorocarbons by altering the atmospheric temperature, and thereby the air density and chemical reaction rates. It postulates that increases in CO_2 and NO_x concentrations may lead to an increase in total ozone. This finding points to the complexity of modeling global-scale chemical and climatic effects.

Z. Zhang, S. Padmaja, R. D. Saine, R. E. Huie, and M. J. Kurylo (National Institute of Standards and Technology, NIST), **Reactions of Hydroxyl Radicals with Several Hydrofluorocarbons: The Temperature Dependencies of the Rate Constants for $CHF_2CF_2CH_2F$ (HFC-245ca), $CF_3CHFCHF_2$ (HFC-236ea), CF_3CHFCF_3 (HFC-227ea), and $CF_3CH_2CH_2CF_3$ (HFC-356ffa)**, *Journal of Physical Chemistry*, 98(16):4312-4315, 21 April 1994 (4 pages with 3 figures and 2 tables, RDB5804)

R-227ea, R-236ea (CHF_2CHFCF_3), R-245ca ($CH_2FCF_2CHF_2$), and R-356mff ($CF_3CH_2CH_2CF_3$, identified in the paper as R-356ffa or HFC-356ffa)

Z. Zhang, R. D. Saine, M. J. Kurylo, and R. E. Huie (National Institute of Standards and Technology, NIST), **Rate Constants for the Reactions of the Hydroxyl Radical with Several Partially Fluorinated Ethers**, *Journal of Physical Chemistry*, 96(23):-9301-9304, 1992 (4 pages, rdb5551)

tropospheric lifetime of R-E125, R-E134, R-E143a, R-CE216 and others - as reported in RDB7B15

Alternative Fluorocarbons Environmental Acceptability Study, AFEAS, Washington, DC, 1997 (36 pages with 7 figures and 3 tables, RDB7A46)

This booklet presents eleven summaries addressing the environmental aspects of alternative fluorochemicals, including those used as refrigerants. The first two summarize the cooperative research efforts by industry under the *Alternative Fluorocarbons Environmental Acceptability Study* (AFEAS) and *Programme for Alternative Fluorocarbon Toxicity Testing* (PAFT), to examine the acceptability hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) as chlorofluorocarbon (CFC) replacements. A summary of the *Montreal Protocol on Substances that Deplete the Ozone Layer* reviews the history of this international accord to phase out production of CFC and HCFC refrigerants among other chemicals. It also recaps the schedules under the Protocol as well as the U.S. Clean Air Act and European regulations. A summary on *Production and Sales of Fluorocarbons* reviews and provides a plot of the worldwide production of R-11, R-12, R-22, R-113, R-114, R-115, R-134a, R-141b, and R-142b for 1980-1995. It highlights key changes in production between 1994 and 1995 and shows a plot of CFC production by year on an ozone depletion potential (ODP) weighted basis. A summary on *Atmospheric Chlorine: CFCs and Alternative Fluorocarbons* reviews the mechanisms of stratospheric ozone depletion and plots the ODP values used in the Montreal Protocol and projected chlorine-bromine loading (CBL, identified as equivalent halogen loading) through the year 3000. A synopsis of the *Contributions of Greenhouse Gas Emissions to Climate Forcing Relative to CO_2* discusses radiative forcing, a parameter used to describe the perturbation of the heat balance in modeling the earth-atmosphere system. It explains the basis for global warming potentials (GWPs) and the quantitative influence of *integration time horizon* (ITH) on analyses of impacts. A table provides estimates for the atmospheric lifetimes and GWP values for 20, 100, and 500 yr ITH. A sheet on *Total Global Warming Impact and TEWI* explains the significance of direct (emission related) and indirect (energy related) effects of alternative technologies and fluids. Two plots show the radiative forcing associated with the direct (refrigerant and insulation blowing agent) and indirect components of use of a refrigerator freezer. The discussion notes that the direct effect is much smaller and eliminated within 100 years, whereas significant carbon dioxide from the associated energy production persists more than 500 years later. The summary discusses the outlook for "not-in-kind" alternative technologies, suggesting that efficiency improvement for conventional technologies is more promising to mitigate future climate change. A review of the *Breakdown Products of Alternatives* outlines the mechanisms and consequences of CFC, HCFC, and hydrofluorocarbon (HFC) breakdown. It notes that they readily decompose into simple inorganic species in the lower atmosphere, that the ultimate breakdown products are acidic compounds that are washed out in rain, that the acidic concentrations are so low as to have no appreciable effect, and that the alternatives do not contribute to photochemical smog formation in urban areas. A further summary of the *Environmental Fate of Trifluoroacetyl Halides* addresses the atmospheric breakdown of R-123, R-124, and R-134a, producing trace quantities of trifluoroacetyl halides. These halides hydrolyze, in cloud water droplets or surface waters, to form trifluoroacetic (TFA) acid and hydrofluoric or hydrochloric acid. The fate of TFA ions is discussed. While not expected to have an impact on humans, plants, animals, or microorganisms, further study of the ultimate physiochemical and biological fate is underway. A summary on *TFA and Seasonal Wetlands* responds to a published analysis that suggests TFA buildup in transient wetlands. The summary outlines factors that may enhance local TFA concentrations in rain and in wetlands. It also discusses the assumptions used in the analyses and interprets the findings. A sheet on *UV-B Radiation Measurements* discusses the importance of the ozone layer in shielding ultra-violet-B (UV-B) radiation in sunlight as well as efforts to monitor and observed trends of incoming UV-B intensity. A *Glossary of Terms* defines terminology for discussion of the atmospheric effects of alternative fluorocarbons.

Chemical Kinetics and Photochemical Data for Use in Stratospheric Modeling, report 94-26, Jet Propulsion Laboratory (JPL), California Institute of Technology, 1994 (rdb8105)

alternative refrigerants, lifetime, atmospheric reactions

Emissions of Greenhouse Gases in the United States, 1997, report DOE/EIA-0573(97), Energy Information Administration, U.S. Department of Energy, Washington, DC, October 1998 (166 pages with 11 figures and 62 tables, available from GPO as document 061-003-01047-4, limited copies available from JMC as RDB8A01)

estimated emissions in the USA of carbon dioxide (R-744), methane (R-50), nitrous oxide (R-744A), halocarbons, sulfur hexafluoride (R-7146), criteria pollutants (carbon monoxide, nitrogen oxides, and nonmethane volatile organic compounds, VOCs), and other greenhouse gases: the halocarbons addressed include R-10 (carbon tetrachloride), R-11, R-12, R-14, R-22, R-23, R-30 (methylene chloride), R-113, R-116, R-125, R-134a, R-140a (methyl chloroform), R-141b, R-142b, R-143a, R-152a, R-227ea, R-31-10, and R-43-10; limited data or discussion also are provided for halons, R-20 (chloroform), R-114, R-115, R-123, R-124, and R-236fa; the halocarbon data are presented collectively for the bromofluorocarbon (BFC, halon) and individually and collectively for the chlorofluorocarbon (CFC), hydrochlorofluorocarbons (HCFC), hydrofluorocarbons (HFC), perfluorocarbon (HFC) groups; depending on the substance, data cover the period from 1989 through 1997; estimated emissions are from all uses - refrigerant components are a small fraction of the total; report identifies the data sources, conversion methods, and limitations

Greenhouse-Gas-Induced Climatic Change: A Critical Appraisal of Simulations and Observations (proceedings of a Workshop on Greenhouse-Gas-Induced Climatic Change, University of Massachusetts, Amherst, MA, 8-12 May 1989), edited by M. E. Schlesinger, Elsevier Science Publishers

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B.V., Amsterdam, The Netherlands, 1992 (615 pages, rdb3973)

global warming, greenhouse gases, environmental impact

Guideline Methods of Calculating TEWI, a BRA Specification, British Refrigeration Association, Bourne End, UK, 1996 (rdb8608)

standard methods to calculate the total equivalent warming impact (TEWI) for refrigeration-related uses of substances that behave as greenhouse gases, including refrigerants

Handbook of Environmental Fate and Exposure Data for Organic Chemicals, edited by P. H. Howard, 1989-1993 (4 volumes totaling more than 2400 pages, rdb6105)

release, transport, and degradation of organic compounds

Production, Sales and Atmospheric Release of Fluorocarbons through 1996, Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), Washington, DC, 1998 (124 pages with 3 figures and 47 tables, RDB8B35)

R-11, R-12, R-22, R-113, R-114, R-115, R-124, R-134a, R-141b, R-142b, production and emission data

Scientific Assessment of Ozone Depletion: 1998, chaired by D. L. Albritton, P. J. Aucamp, G. Mégie, and R. T. Watson, report 44, World Meteorological Organization (WMO), Global Ozone Research and Monitoring Project, Geneva, Switzerland; United Nations Environment Program (UNEP), Nairobi, Kenya; National Oceanic and Atmospheric Administration (NOAA), Washington, DC, USA; National Aeronautics and Space Administration (NASA), Washington, DC, USA; and the European Commission, Directorate General XII - Science, Research and Development, Brussels, Belgium; February 1999 (736 pages with 264 figures and 63 tables, available from WMO, RDB9501)

This definitive work, the seventh in a series, updates the assessment used in governmental and international decision-making for protection of the stratospheric ozone layer. The volume addresses common questions about ozone depletion, observed changes in ozone and source gases, atmospheric processes responsible for these changes, simulations of global ozone, consequences of ozone change, and scientific information for future decisions. It was prepared by 13 international panels, consisting of 230 of the world's leading experts in the atmospheric sciences, and subjected to an intensive peer review by 147 scientists. The product summarizes understanding of the stratospheric ozone layer and its relation to humankind. The assessment was initiated in November 1992 by the 4th meeting of the parties to the Montreal Protocol in Copenhagen. The results are scheduled for consideration by the parties to the Protocol, for potential revision of the Protocol in 1995 at the 5th meeting in Vienna. The report provides internationally recognized values for atmospheric lifetimes, response times, chlorine and bromine loading, ozone depletion potential (ODP), and global warming potential (GWP) for natural and anthropogenic chemicals impacting the global environment.

Scientific Assessment of Ozone Depletion: 1998 - Executive Summary, chaired by D. L. Albritton, P. J. Aucamp, G. Mégie, and R. T. Watson, report 44, World Meteorological Organization (WMO), Global Ozone Research and Monitoring Project, Geneva, Switzerland; United Nations Environment Program (UNEP), Nairobi, Kenya; National Oceanic and Atmospheric Administration (NOAH), Washington, DC, USA; National Aeronautics and Space Administration (NASA), Washington, DC, USA; and the European Commission, Directorate General XII - Science, Research and Development, Brussels, Belgium; February 1999 (48 pages with 10 figures and 1 table, available from WMO, RDB9502)

This report summarizes the definitive assessment used in governmental and international decision-making for protection of the stratospheric ozone layer. The volume addresses the major scientific findings and observations, supporting evidence, related issues, and implications. The second portion responds to common questions about ozone depletion. It discusses how chlorofluorocarbons get to the stratosphere, evidence of stratospheric ozone destruction by chlorine and bromine, and that the majority of the chlorine in the stratosphere comes from human-made (anthropogenic) sources. It also examines whether changes in the sun's output could be responsible, the first appearance of the Antarctic ozone hole, and why it occurred there rather than over the northern hemisphere. The summary concludes with discussion of the increase in ground-level ultraviolet radiation, the severity of the ozone depletion, and whether it will get worse. The executive summary and underlying report summarize understanding of the stratospheric ozone layer and its relation to humankind.

The Changing Pattern of Use of Fluorocarbons in the European Community 1976-1994, European Chemical Industry Council (CEFIC), Brussels, Belgium, 1995 (rdb8B36)

production data and trends

REGULATORY ACTIONS

W. J. Clinton and A. Gore, **The Climate Change Action Plan,** The White House, Washington, DC, October 1993 (134 pages with 2 figures and 2 tables, available from GPO, limited copies available from JMC as RDB4208)

CCAP

The Climate Change Action Plan: Technical Supplement, report DOE/PO-0011, U.S. Department of Energy (DOE), Washington, DC, March 1994 (164 pages with 18 figures and 37 tables, available from NTIS, limited copies available from JMC as RDB4671)

CCAP

International

1994 Report of the Refrigeration, Air Conditioning, and Heat Pumps Technical Options Committee for the 1995 Assessment, chaired by L. J. M. Kuijpers, United Nations Environment Programme (UNEP), Ozone Secretariat, Nairobi, Kenya, 30 November 1994 (326 pages with 8 figures and 72 tables, available from JMC as RDB5274)

This report is one of seven prepared to assess the status of technologies impacted by the Montreal Protocol and to assess whether the control measures of the Protocol are sufficient to meet the goals of reducing ozone depletion. It is based on a review of the current state of knowledge on technical, scientific, environmental, and economic issues related to stratospheric ozone protection. The Technical Options Committee (TOC) examined options and trends for achieving compliance and assembled projections for refrigerant uses. The peer-reviewed report was prepared, pursuant to Article 6 of the Protocol, by an international panel representing approximately 100 firms, organizations, and government agencies and 22 countries. It addresses the Protocol and reassessment procedure, refrigerant data, domestic refrigeration (including refrigerators and other appliances), commercial refrigeration, cold storage and food processing, industrial refrigeration, air conditioning and heat pumps, chillers, transport refrigeration, and mobile air conditioning, mobile air conditioning, heating-only heat pumps and heat recovery, refrigerant conservation, developing country aspects, research coordination and information dissemination, historical chlorofluorocarbon (CFC) consumption and future demand and supply, historical hydrochlorofluorocarbon (HCFC) consumption and future demand, and alternative refrigeration technologies.

1997 Update of the Handbook for the International Treaties for the Protection of the Ozone Layer, United Nations Environment Programme (UNEP), Ozone Secretariat, Nairobi, Kenya, 1998 (260 pages, RDB8C01)

This document contains the complete texts of the Vienna Convention and the Montreal Protocol as amended. These international treaties are formally titled the *Vienna Convention for the Protection of the Ozone Layer* and the *Montreal Protocol on Substances that Deplete the Ozone Layer*. They are administered under the auspices of the United Nations Environment Programme (UNEP). Together with the handbook [see RDB6904], the update summarizes the resulting control measures, the signature and ratification status by treaty and amendment for the 165 Parties (countries plus the European Union) that have adopted them, and the rules of procedure for meetings of the Parties. The decisions of the Parties and annexes to the Montreal Protocol, that relate to its interpretation, at meetings in Helsinki in (April-May 1989), London (June 1990), Nairobi (June 1991), Geneva (July 1992), Copenhagen (November 1992), Bangkok (November 1993), Nairobi (October 1994), Vienna (December 1995), San Jose (November 1996), and Montreal (September 1997) are presented and indexed to the Articles to which they pertain. The handbook and update list approved destruction procedures and essential use exemptions, composition and procedures (terms of reference) for scientific and economic assessment panels, remedies for noncompliance, procedures for and details of the Interim Multilateral Fund and Multilateral Fund to assist Article 5 (developing) countries, finance of and procedures for the Trust Fund for administration of the treaties, and declarations adopted from 1989 through 1995. They include the *Helsinki Declaration on Protection of the Ozone Layer* (1989); declarations by Australia, Austria, Belgium, Canada, Denmark, Finland, Germany, Liechtenstein, Netherlands, New Zealand, Norway, Sweden, and Switzerland on advancing the phase out of chlorofluorocarbons (CFCs) to not later than 1997 (1990); a resolution on more stringent measures for ozone depleting substances (1990); statements by Austria, Denmark, Germany, Finland, Norway, Sweden, and Switzerland on more control measures (1991); a resolution on methyl bromide (1992); statements on representation of Yugoslavia (1992); a memorandum on hydrochlorofluorocarbons (HCFCs) (1993); and declarations on methyl bromide (1993), by countries with economies in transition (1993), on the Multilateral Fund

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(1994), on HCFCs (1995), and methyl bromide (1995). The update then lists sources, contacts, and publications for further information, primarily from United Nations and international organizations. A concluding section presents the evolution of the Montreal Protocol from its original text through successive amendments. The Vienna Convention was adopted on 22 March 1985 and entered into force on 22 September 1988. The Montreal Protocol was adopted on 16 September 1987 and entered into force on 1 January 1989, the London Amendment 29 June 1990 and 10 August 1992, the Copenhagen Amendment on 23 November 1992 and 14 June 1994, and the Montreal Amendment on 15-17 September 1992 and 1 January 1999. Entry into force follows ratification, accession, acceptance, or approval by prescribed numbers of Parties.

National

Code of Practice for the Reduction of Chlorofluorocarbon Emissions from Refrigeration and Air Conditioning Systems, document EPS1/RA/1, Environment Canada, Ottawa, Ontario, Canada, March 1991 (27 pages, RDB3218)

Refrigeration Safety Regulation, translated by the Japan Refrigeration and Air Conditioning Industry Association (JRAIA), Tokyo, Japan, circa 1990 (36 pages, RDB1132)

refrigerant safety, Japanese High-Pressure Gas Control Law (law number 204 of 1951), R-12, R-13, R-14, R-21, R-22, R-40, R-170, R-290, R-500, R-502, R-600, R-600a, R-717, R-1150, and others

SUBSTITUTE REFRIGERANTS

R. Aarlien, J. Pettersen, G. Skaugen, and P. Nekså (SINTEF Energy Research, Norway), **A Comparative Evaluation of CO_2 and HCFC-22 Residential Air-Conditioning Systems in a Japanese Climate**, *Proceedings of the IIR Conference on Applications for Natural Refrigerants* (Århus, Denmark, 3-6 September 1996), International Institute of Refrigeration (IIR), Paris, France, 659-666, September 1996 (5 pages, rdb9234)

R-744 (carbon dioxide)

U. Adolph, **Possibilities and Limits of Using Natural Refrigerants in Air-Conditioning Systems for Railway Cars**, *New Applications of Natural Working Fluids in Refrigeration and Air Conditioning* (proceedings of the meeting of IIR Commission B2, Hannover, Germany, 10-13 May 1994), International Institute of Refrigeration (IIR), Paris, France, 477-487, 1994 (11 pages, rdb9926)

M. Arnemann, D. Gebhardt, and H. H. Kruse (Universität Hannover, Germany), **Experimentelle Bewertung neuer Kältemittelgemische als Ersatz für R22 and R502** [Experimental Evaluation of New Refrigerant Mixtures as Replacements for R-22 and R-502], *KK Die Kälte- und Klimatechnik*, Germany, 48(2):66 ff., 1995 (in German, rdb8C13)

performance tests of blends

M. Barreau (Elf Atochem S.A., France), **Present European Environmentally-Friendly HCFC Substitutes in Stationary Air Conditioning,** *The Earth Technologies Forum* (proceedings, Washington, DC, 26-28 October 1998), Alliance for Responsible Atmospheric Policy, Arlington, VA, 206-214, October 1998 (9 pages with 3 figures, RDB8B17)

status of substitutes in Europe with focus on R-32, R-125, R-134a, R-143a, and blends containing them, notably R-404A, R-407C, and R-410A: outlines phaseout schedules for chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) and replacement projections

K. Berglöf (AKA Kyla AB, Sweden) and J. Morley (DuPont Fluoroproducts, UK), **Practical Experience in the Use of R-407C in Small Chillers and Heat Pumps in Sweden**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 7-12, July 1996 (6 pages with 2 figures and 1 table, RDB-6747)

results from developmental, laboratory testing of R-407C in low-charge chiller systems; concludes that R-407C is a viable substitute for R-22 in direct expansion systems including ground-source heat pumps; notes that approximately 1500 heat pumps using R-407C are in operation in Sweden

M. S. Bhatti, **A Critical Look at R-744 and R-134a Mobile Air Conditioning Systems**, paper 970527, SAE International Congress and Exposition (Detroit, MI), Society of Automotive Engineers (SAE), Warrendale, PA; republished in *Automotive Climate Control Design Elements*, special publication 1239, SAE, 117-141, 1997 (25 pages, rdb8349)

comparison of R-134a and R-744 (carbon dioxide) in mobile air-conditioning (MAC) systems

D. B. Bivens and B. H. Minor (E. I. DuPont de Nemours and Company), **Fluoroethers and Other Next-Generation Fluids**, *Refrigerants for the 21st*

Century (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 122-134, 1997 (13 pages with 3 figures and 1 table, RDB7B15)

review of candidate fluorinated ethers (HFE), alcohol, amine, silicon, and sulfur compounds: provides an extensive tabular summary including formulae, normal boiling points, atmospheric lifetimes, flammability indications (ratios of substituent fluorine to fluorine plus hydrogen counts), toxicity, and stability; several potential alternatives are identified for further study, but the effort and expense necessary to qualify a new refrigerant are described as enormous; based on current information, none of the candidates appears to have the balance of performance, safety, environmental characteristics, ease of manufacture, and cost needed to challenge hydrofluorocarbons (HFCs), but further opportunities may be identified by relating properties to molecular structures

E. Bodio, M. Chorowski, and M. Wilczek (Technical University of Wroclaw, Poland), **Propane-Butane A Promising Alternative**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:762-765, 1995 (4 pages with 1 figure and 2 tables, rdb7916)

findings of a five-year test of retrofits of domestic refrigerators to R-290/600: concludes that R-290/600 (50/50 molar) is an excellent alternative for retrofit of domestic refrigerators where flammability creates no danger; moreover, the hydrocarbon blend is an attractive choice in countries with developing economies, where users cannot afford more-expensive options or replacement; paper notes that unless an inexpensive and environmentally-friendly service refrigerant is allowed, illegal trade in R-12 is likely

H. Brandes (Forschungszentrum für Kältetechnik und Wärmepumpen, FKW, Germany), R. Heidelck (Universität Hannover, Germany), H. H. Kruse (FKW), **High-Temperature Industrial and Residential Heat Pumps,** *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, presentations tab 24, 1999 (26 pages with 17 figures and 2 tables, RDB9837)

H. Brandes (Forschungszentrum für Kältetechnik und Wärmepumpen, FKW, Germany), R. Heidelck (Universität Hannover, Germany), J. Süß (FKW), H. Kruse (FKW), **Development of a Residential Heating-Only Heat Pump for High-Temperature Hydronic Systems,** *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 30, 1999 (22 pages with 25 figures and 12 tables, RDB9876)

outlines development of a prototype heat pump using R-744 (carbon dioxide) in a transcritical cycle to achieve high efficiency and high temperatures for hydronic delivery systems under the COHEPS Project; describes a cycle analysis, the components including open reciprocating-piston compressors from Bock Kältemaschinen GmbH and Danfoss A/S, system control, and prototype design and construction; summarizes tests with two air-to-water prototypes at constant gas cooler pressure of 10.5 MPa (1500 psia) and at optimum gas cooler pressure - varied from 11.0 MPa (1600 psia) at -5 °C (23 °F) ambient temperature to 8.7 MPa (1300 psia) at 10 °C (50 °F) ambient temperature; also summarizes comparative tests with a 7 kW (24 Mbh) KKW GmbH "Dimplex W17C" heat pump using R-407C; comparison shows that the R-407C system yielded a significantly higher coefficient of performance (COP) at the four conditions tested, but the paper notes that prototype used an inverter, had a water-cooled motor for which no credit was taken for motor heat, and was not fully optimized; concludes that the results are promising, but that the inverter-motor combination, compressor, and heat exchangers have to be improved and an R-744 expansion device developed to improve the efficiency

C. E. Bullock (Carrier Corporation), **Assessment of Carbon Dioxide as a Refrigerant**, *Tech Update*, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 5(5):1-2, September 1996 (2 pages with 2 figures, available from JMC as RDB6A02)

R-744, carbon dioxide, possibilities and limitations for use in unitary air conditioners and heat pumps; cycle efficiency; plots compare the coefficient of performance and operating pressure ratio against evaporating temperature, based on isentropic compression, for R-22, R-134a, R-744, and the Carnot cycle; expansion options including expanders; concludes that R-744 offers the advantages of low toxicity and cost, nonflammability, and wide availability, but its inherently low efficiency and high operating pressures will remain serious challenges in the near term

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D. Butler and T. Fannin, **Trials with New HFC Based Refrigerants**, Refrigerants for Air Conditioning: Options for Change (CIBSE Conference), CIBSE, UK, May 1994 (RDB9602)

A. Cavallini (Università di Padova, Italy) and F. Steimle (Universität Essen), **Natural Working Fluids in a Historic Perspective,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 37-42, 1998 (6 pages with no figures or tables, RDB9201)

> reviews early, historical use of R-717 (ammonia), R-718 (water), R-729 (air), R-744 (carbon dioxide), R-764 (sulfur dioxide), and hydrocarbons as refrigerants; cites early developments by Jacob Perkins, John Gorrie, Kirk, Franz Windhausen, P. Giffert, W. Cullen, E. Carré, Maurice LeBlanc, Beaumont, C. Parsons, McCord, G. Maiuri, F. Carré, E. Altenkirch, Merkel-Bosnjakovic, David Boyle, Karl von Linde, A. Audifren, Thilorier, and Thaddeus S. C. Lowe

J. Chen, K. Beermann, and H. H. Kruse (Universität Hannover, Germany), **R227. An Environmentally Benign Refrigerant for High Temperature Heat Pump Applications**, *CFCs, the Day After* (proceedings of the IIR meeting, Padova, Italy, 21-23 September 1994), International Institute of Refrigeration (IIR), Paris, France, 133-145, September 1994 (13 pages, rdb9319)

> R-227ea

J. M. Corberán, J. F. Urchueguía (Universidad Politécnica de Valencia, Spain), M. Conde (Manuel Conde Engineering, Switzerland), T. Setaro (Ente per le Nuove Tecnologie, l'Energia, e l'Ambiente, ENEA, Italy), L. Sartori (Alfa Laval - Artec Spa, Italy), E. Granryd, B. Palm (Kungliga Tekniska Högskolan, KTH, Sweden), J. Sáez, A. Ramos (Compañia Industrial de Aplicaciones Técnicas S.A., Spain), and J. de Blás (Asociación Española para la Diagnosis y la Investigación en Energía, AEDIE, Spain), **Optimization of a Commercial, Medium size, Reversible Heat Pump for Use with Propane**, *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 31, May 1999 (9 pages with 4 figures, RDB9877)

> outlines the European Commission HEAHP/J3 Project to develop a reversible air-to-water heat pump for use with R-290 (propane) for use in southern European countries with high air-conditioning loads; indicates that the work is starting with adaption and optimization of a 20 kW (5.7 ton) R-22 heat pump from CIATESA; summarizes the project objectives, construction of a test apparatus, and component and system modeling

S. Corr, J. D. Morrison, F. T. Murphy, and R. L. Powell (ICI Klea, UK), **Developing the Hydrofluorocarbon Range: Fluids for Centrifugal Compressors,** *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:131-138, 1995 (8 pages with 3 figures and 1 table, RDB-7733)

> application of approximate relationships between molecular structure and the macroscopic properties of a fluid to identify candidate refrigerants for centrifugal compressors; tabulates the normal boiling point, flammability and molecular mass of R-11, R-113, R-114, R-E236ea1, R-236fa, R-E236fa1, R-245ca, R-245ca1, R-E245cb1, R-245fa, R-E245fa1, R-E254cb1, R-329pcc (identified in the paper as R-329cca), R-E329pcc1 (identified as R-E329cca1), R-C336, R-338mcf (identified as R-338cfa), R-E338mfc2 (identified as R-E338cfa2), R-338eea, R-E347mfc2, R-E347scc1, R-365fcb, R-356mff (identified in the paper as R-356ffa), R-43-10meec (identified as R-410mee); concludes that a compromise may be needed between flammability and thermodynamic performance for hydrofluorocarbons (HFCs), based on the conflicting advantages of high hydrogen content for performance and high fluorine content to avoid flammability

P. D. de Larminat (York International, France), **New Developments to Expand the Use of Ammonia**, *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 80-84, 1997 (5 pages with no figures or tables, RDB7B09)

> use of R-717 (ammonia)

J. D. Douglas (AIL Research, Incorporated), E. A. Groll, J. E. Braun, and D. R. Tree (Purdue University), **Evaluation of Propane as an Alternative to HCFC-22 in Residential Applications**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 13-20, July 1996 (8 pages with 5 figures, RDB6748)

> R-290, R-290/227ea, cost-based evaluation of propane and propane-blends in comparison to R-134a, R-407C, R-410A, R-32/134a, R-32/125/-134a, and R-32/125a as replacements for R-22

S. Engelking and H. H. Kruse (Forschungszentrum für Kältetechnik und Wärmepumpen GmbH, FKW, Germany), **Development of Air Cycle Technology for Transport Refrigeration,** *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 349-356, July 1996 (8 pages with 7 figures and 2 tables, RDB6929)

R-729 (air), air-cycle refrigeration, turbine-compressor/turbine-expander and pressure-wave prototypes; performance comparison to R-22 vapor-compression cycle equipment; concludes that the pressure-wave machine (PWM) is preferable to the turbo expander and compressor approach for efficiency and cost

T. Enkemann and H. H. Kruse (Forschungszentrum für Kältetechnik und Wärmepumpen, FKW, Germany), **Operation Control of a CO_2 Heat Pump for Application in Existing Heating Systems**, *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 148-155, 1997 (8 pages with 6 figures, RDB9329)

describes the cycle used and control scheme developed for a transcritical cycle using R-744 (carbon dioxide) as the refrigerant in an air-to-water heat pump for a hydronic heating system

T. Enkemann, H. H. Kruse (Forschungszentrum für Kältetechnik und Wärmepumpen, FKW, Germany), and P. A. Oostendorp (Netherlands Organization for Applied Scientific Research, TNO, The Netherlands), **CO_2 as a Heat Pump Working Fluid for Retrofitting Hydronic Heating Systems in Western Europe**, *CO_2 Technology in Refrigeration, Heat Pump, and Air-Conditioning Systems* (proceedings of the IEA-HPC/IIR Workshop, Trondheim, Norway, 13-14 May 1997), International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, and the International Institute of Refrigeration (IIR), Paris, France, 1997 (rdb9330)

R-744, mobile air-conditioning (MAC) systems

B. E. Fagerli (Norwegian University of Science and Technology, NTNU, Norway), **Theoretical Analysis of Compressing CO_2 in Scroll Compressors**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 249-259, 1998 (11 pages with 11 figures and 3 tables, RDB9220)

analyzes the internal leakage paths in scroll compressors for R-744 (carbon dioxide) in comparison to R-134a; suggests design changes to address tip and flank clearance in scroll design to improve performance; includes discussion by H. Kruse (Forschungszentrum für Kältetechnik und Wärmepumpen GmbH, FKW, Germany) and R. Caesar (Daimler-Benz AG, Germany)

B. E. Fagerli (Norwegian University of Science and Technology, NTNU, Norway), **CO_2 Compressor Development,** *CO_2 Technology in Refrigeration, Heat Pump, and Air-Conditioning Systems* (proceedings of the IEA-HPC/IIR Workshop, Trondheim, Norway, 13-14 May 1997), International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, and the International Institute of Refrigeration (IIR), Paris, France, 1997 (rdb9243)

R-744 (carbon dioxide)

K. Furuhama, H. Motohashi, S. Hayano, and T. Sano (Toshiba Corporation, Japan), **Alternative Refrigerants in Air Conditioners for Residential and Commercial Use**, *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, presentations volume tab 11, May 1999 (8 pages with 8 figures and 3 tables, RDB-9833)

R-22, R-32, R-290 (propane), R-407C, R-410A, and R-744 (carbon dioxide)

G. R. Giles, R. G. Hunt, and G. F. Stevenson (Normalair Garrett Limited, UK), **Air as a Refrigerant for the 21st Century**, *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 96-103, 1997 (8 pages with 14 figures, RDB7B11)

R-729 (air), concludes that air-cycle refrigeration is less efficient than conventional vapor-compression systems, but that improvements in component efficiencies may enable use; discusses applications in aerospace and surface transportation, automobiles, buildings, and food freezing and preserving

S. Goktun (Istanbul Technical University, Turkey), **Overview of Chlorine-Free Refrigerants for Centrifugal Chillers**, *Energy*, 20(9):937-940, September 1995 (4 pages, rdb8208)

describes criteria for ideal working fluids in centrifugal chillers; compares the environmental and thermophysical properties of candidates;

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identifies R-245ca and R-E245fa as promising alternatives to R-11 for the low-capacity range, and R-134a as the best retrofit refrigerant for R-12 in medium capacities; identifies R-236ca, R-236cb, R-236ea, R-236fa, and R-E134 as promising refrigerants to replace R-114 in high-capacity chillers

S. Gopalnarayanan (Elf Atochem North America, Incorporated) and R. K. Radermacher (University of Maryland), **Heat Pump Assisted Dryer Using Refrigerant Mixtures - Batch Mode Drying,** paper PH-97-12-3, *Transactions* (Winter Meeting, Philadelphia, PA, 26-29 January 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 103(1):888-895, 1997 (8 pages with 9 figures and 3 tables, RDB-7C25)

R-134a, R-32/134a (33.77/66.23) [50/50 molar]

X-Z. Guo and J-J. Zhang (Zhejiang Chemical Industry Research Institute, ZCIRI, China), **Prospect for HFC-152a-Based Mixtures as CFC-12 Alternative**, *The Earth Technologies Forum* (proceedings, Washington, DC, 26-28 October 1998), Alliance for Responsible Atmospheric Policy, Arlington, VA, 179-185, October 1998 (7 pages with 3 tables, RDB8B15)

compares environmental, performance, safety, and application factors for R-134a, R-152a, R-600a (isobutane), R-22/152a, R-32/152a, R-125/152a, R-143a/152a (possibly R-134a/152a - text contradicts table), and R-290/152a use as refrigerants in domestic refrigerators; identifies two R-22/152a blends that are commercially used in China, namely ZC-1 and ZC-2; indicates that R-32/152a shows promise for future use [the blend formulations are not given and inconsistencies in the data preclude precise determination, but the ZC and "promising" blends appear to be approximately R-22/152a (23/77), R-22/152a (58/42), and R-32/152a (6/94)]

N. P. Halm, H. H. Kruse (Forschungszentrum für Kältetechnik and Wärmepumpen, FKW, Germany), S. Bobbo, and R. Camporese (Consiglio Nazionale della Ricerche, CNR, Italy), **Heat Pump Control with Zeotropic Mixtures**, *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, presentations tab 19, 1999 (13 pages with 22 figures and 3 tables, RDB9836)

K. Hashimoto and M. Saikawa (Central Research Institute of Electric Power Industry, CRIEPI, Japan), **CO_2 as a Working Fluid for Heat Pump**, *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May -2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 20, 1999 (7 pages with 8 figures and 7 tables, RDB9872)

presents a cycle analysis for a heat pump using R-744 (carbon dioxide) in a transcritical cycle; discusses the characteristics and control methods for this cycle; outlines heat transfer tests of the gas cooler; concludes that R-744 can achieve a coefficient of performance (COP) approximately 15% higher than R-22 for water heating; identifies research needs including further study of cycle control, heat transfer, and properties for R-744

U. Hesse, M. Kauffeld, and J. Pettersen (Universität Hannover, Germany) **Kohlendioxid - CO_2 - in der Kälte-, Klima-, und Wärmepumpentechnik** [Carbon Dioxide - CO_2 - in Refrigeration, Air Conditioning, and Heat Pumps], *Die Kälte- und Klimatechnik,* Germany, 46(11):762 ff., 1993 (in German, rdb9324)

use of R-744 (carbon dioxide) as a refrigerant

P. Heyl, W. E. Kraus, and H. Quack (Technische Universität Dresden, Germany), **Expander-Compressor for a More Efficient Use of CO_2 as Refrigerant**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 240-248, 1998 (9 pages with 8 figures and 2 tables, RDB9219)

presents calculated coefficients of performance (COPs) for single- and two-stage cycles with circuit modifications to increase efficiency by recovering expansion work including use of expanders; proposes use of the "full pressure principle" in a "Volldrucksmaschine" with a free-piston expander-compressor unit; indicates that the approach offers flexibility over a broad range of operation and 78% recovery compared to complete expansion

Y. H. Hwang, **Comprehensive Investigation of Carbon Dioxide Refrigeration System**, PhD dissertation, Department of Mechanical Engineering, University of Maryland, College Park, MD, 1997 (rdb9237)

summarizes theoretical and experimental investigations of R-744 (carbon dioxide) as a refrigerant

A. Jakobsen (Norgest Tekniska Högskole, NTH, Norway) and P. Nekså (SINTEF Energy Research, Norway), **Carbon Dioxide in Marine Refrigeration Applications,** *The Earth Technologies Forum* (proceedings, Washington, DC, 26-28 October 1998), Alliance for Responsible Atmospheric Policy, Arlington, VA, 153-162 (repeated 163-172), October 1998 (10 pages with 11 figures and 4 tables, RDB-8B14)

simulated performance of R-744 (carbon dioxide) in transcritical cycles for refrigerated shipping containers (RC) and ships ("reefers"); calculations indicate lower energy consumption compared to systems using R-22 or R-134a; identifies an ejector and expander system to further reduce energy use; notes that R-744 was the dominant refrigerant in these applications until 1955 (now dominantly R-22) and suggests that its use should be resumed for environmental reasons; indicates an average refrigerant loss rate of 20 %/yr in these systems

H. Kaiser (Forschungszentrum für Kältetechnik und Wärmepumpen GmbH, FKW, Germany), **Verdichter für natürliche Kältemittel in Nutzfahrzeugen und Omnibussen** [Compressor for Natural Refrigerants in Utility Vehicles and Omnibuses], *Ki Luft- und Kältetechnik,* 32(8):353 ff., August 1996 (in German, RDB9327)

compressor design for use of R-744 (carbon dioxide) and hydrocarbons as refrigerants in mobile air-conditioning (MAC) systems

G. Kasper and H. Halozan (Technische Universität Graz, Graz, Austria), **CO_2 - An Old Refrigerant,** *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 121-127, 1997 (7 pages with 5 figures, RDB9320)

presents the design and construction of a prototype 20 kW (68 Mbh) heat pump water heater (HPWH) using R-744 (carbon dioxide) as the refrigerant; key components include a two-cylinder, open-drive, reciprocating-piston compressor (Bock), a counter-flow gas cooler [condenser] consisting of finned copper tubes (Wieland), a similar evaporator, a similar internal heat exchanger, a steel accumulator, and a manually-operated throttling valve; describes a test rig and plan

M. Kauffeld (Universität Hannover, Germany), **Ammoniak, Kohlendioxid und Wasser - die gewirblicher Kältemittel der Zukunft**, [Ammonia, Carbon Dioxide and Water - the Commercial Refrigerants of the Future], *Die Kälte,* Germany, (5):, 1995 (in German, rdb9235)

use of R-717 (ammonia), R-718 (water), and R-744 (carbon dioxide) as refrigerants

G. S. Kazachki (Acurex Environmental Corporation) and C. L. Gage (U.S. Environmental Protection Agency, EPA), **Screening of Non-CFC Alternatives for High-Temperature Heat Pumps,** *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 105-111, 1997 (7 pages with 3 figures and 1 table, RDB9317)

discusses the relation of specific volumetric capacity (SVC) to equipment size, and therefore cost, and coefficient of performance (COP), and therefore operating cost; derives a screening model based on the SVC and COP to evaluate alternative refrigerants; examines 15 candidate refrigerants for use in high-temperature heat pumps; concludes that R-134a, R-32/134a (22.0/78.0), are R-407D are the preferred refrigerants for condensing temperatures up to 80 °C (176 °F), R-134 for up to 100 °C (212 °F), and R-134/E134 (50.0/50.0) for up to 120 °C (248 °F); provides data for R-114, R-123, R-134, R-E134, R-134a, R-227ea, R-236ea, R-236fa, R-245ca, R-245cb, R-245fa, R-407D, R-32/134a (22.0/78.0) (identified in the paper as "Bin-X"), and R-134/E134 (50.0/50.0) (identified in the paper as "Bin-Z")

G. S. Kazachki (Acurex Environmental Corporation) and C. L. Gage (U.S. Environmental Protection Agency, EPA), **Thermodynamic, Energy-Efficiency, and Economic Criteria for Evaluation of Alternative Refrigerants for Heat Pumps**, *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 71-77, 1997 (7 pages with 3 figures and 1 table, RDB9313)

discusses the relation of specific volumetric capacity (SVC) to equipment size, and therefore cost, and coefficient of performance (COP), and therefore operating cost; derives a screening model based on the SVC and COP to evaluate alternative refrigerants; examines 17 candidate refrigerants for use air conditioners and heat pumps; concludes that R-410A and R-407C are the preferred refrigerants for condensing temperatures up to 55 °C (131 °F) and 75 °C (167 °F), respectively; provides data for them and R-12, R-32, R-125, R-134a, R-143a, R-152a, R-C270 (cyclopropane), R-290 (propane), R-407A, R-407B, R-407D, R-407E, R-507A, and R-32/134a (22.0/78.0) (identified in the paper as "Bin-X")

F. J. Keller (Carrier Corporation), **R-410A Heat Pump Design and Field Experiences in the North American Market**, *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International

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Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, presentations volume tab 10, May 1999 (9 pages with 4 figures and 3 tables, RDB9832)

F. J. Keller, H. Liang, and M. Farzad (Carrier Corporation), **Assessment of Propane as a Refrigerant in Residential Air Conditioning and Heat Pump Applications**, *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 57-65, 1997 (9 pages with 1 figure and 5 tables, RDB7B07)

evaluation of the performance, costs, and environmental impacts of R-290 (propane) in a residential, air-to-air, split-system heat pump and in a window air conditioner; comparisons to R-22 and R-410A

J. Köhler, M. Sonnekalb (Konvecta/IPEK, Germany), H. Kaiser, and B. Lauterbach, **CO_2 for Bus Air-Conditioning and Transport Refrigeration**, *CO_2 Technology in Refrigeration, Heat Pump, and Air-Conditioning Systems* (proceedings of the IEA-HPC/IIR Workshop, Trondheim, Norway, 13-14 May 1997), International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, and the International Institute of Refrigeration (IIR), Paris, France, 1997 (rdb8352)

R-744, mobile air-conditioning (MAC) systems

H. König (Solvay Fluor und Derivate GmbH, Germany), **Systemvergleich für R22-Ersatzstoffe: R407C und R410A** [System Comparison of R-22 Replacements: R-407C and R-410A], *Ki Luft- und Kältetechnik*, 34(10):487-490, October 1998 (4 pages with 3 figures and 1 table in German, rdb-8C03)

discusses theoretical and experimental differences between R-290 (propane), R-407C, and R-410A as replacements for R-22; compares their thermodynamic performance and capacities; presents a new method for fatigue tests [see RDB8B19 for expanded version of this paper in English]

W. E. Kraus and H. Quack (Technische Universität Dresden, Germany), **CO_2 als Kältemittel - Probleme and Potentiale** [CO as a Refrigerant - Problems and Potential], *Ki Luft- und Kältetechnik,* Germany, 30(12):582 ff., 1994 (in German, RDB9325)

use of R-744 (carbon dioxide) as a refrigerant

H. H. Kruse (Forschungszentrum für Kältetechnik und Wärmepumpen, FKW, Germany) and H. König (Solvay Fluor und Derivate GmbH, Germany), **System Comparison of R-22 Replacement Refrigerants,** *The Earth Technologies Forum* (proceedings, Washington, DC, 26-28 October 1998), Alliance for Responsible Atmospheric Policy, Arlington, VA, 225-236, October 1998 (12 pages with 8 figures and 1 table, RDB8B19)

discusses theoretical and experimental differences between R-290 (propane), R-407C, and R-410A as replacements for R-22; compares their thermodynamic performance and capacities; presents a new method for fatigue tests [see RDB8C03 for partial version of this paper in German]

H. H. Kruse and J. Süß (Universität Hannover, Germany), **Research on the Behavior of Refrigeration Compressors Using CO_2 as the Refrigerant**, *Proceedings of the 1996 International Compressor Engineering Conference at Purdue* (23-26 July 1996), edited by W. Soedel, Purdue University, West Lafayette, IN, I:223-228, July 1996 (6 pages with 13 figures and 1 table, RDB9328)

design of a reciprocating-piston compressor for use of R-744 (carbon dioxide) as a refrigerant

S. L. Kwon, J. Berge, and L. Naley (Thermo King Corporation), **Evaluation and Implementation of R-502 Alternatives for Transport Refrigeration**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 63-70, July 1996 (8 pages with 5 figures and 1 table, RDB6761)

reviews the performance requirements for transport refrigeration, outlines a test program for R-404A, R-407A, R-407B, and R-507A; tabulates the composition, molecular weight, critical properties, ozone depletion potentials (ODPs), halocarbon global warming potentials (HGWPs), and flammability for them; describes component modifications; provides plots of the discharge temperatures and pressures and of the comparative fuel consumptions and capacities for R-404A, R-407A, R-407B, and R-507A

H. Lippold and J. Schenk (Institut für Luft- und Kältetechnik Dresden, ILK, Germany), **New Ammonia Refrigeration Engineering by Application of a New Refrigerant Blend and Copper Materials**, *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 14, 1999 (7 pages with 6 figures, RDB9850)

This paper presents data for use of a new blend, R-717/E170 (60.0/40.0) (identified in the paper as "R723"), for refrigeration systems with cooling capacities of approximately 10 kW (2.8 ton). It notes that while R-717 (ammonia) is widely used in large-scale systems, such as ice rinks and cold storage, broader use is limited by toxicity, use of steel and welding in place of copper and brazing common for other refrigerants, design for immiscible lubricants, and measures such as secondary cooling of cylinder heads use of multiple stages to deal with high compressor discharge temperatures. German charge restrictions allow R-717 use without special safety measures in compact systems of up to 25 kW (7.1 ton), but such use is practical only with lubricants that are at least partially soluble in the refrigerant. Blends of R-717 with R-E170 (dimethyl ether, DME), were found to increase lubricant miscibility and to form a maximum azeotrope (one with a higher vapor pressure than either of its components). The azeotrope of R-717/E170 (60/40) has a lower flammability limit (LFL) of 6% v/v, which is higher than for hydrocarbons and results in a flammability group 2 under some classification approaches, achieves higher volumetric cooling performance and improved efficiency compared to ammonia, and improves solubility with mineral oil (MO) and alkylbenzene (AB) lubricants. The paper presents tests of anhydrous ammonia with various lubricants showing acceptable results for most MO lubricants with copper heat exchangers, copper-nickel (CuNi10) piping, phosphorous and silver solders, and bronze alloys, but not with brass. It discusses use of filter driers noting that molecular sieves cannot be used in the liquid phase due to the similar molecular size of water and ammonia and their high polarity, but that molecular sieves could be used in filter driers on the gas phase (on the suction line) with attention to pressure loss. It concludes that the proposed blend offers opportunities to broaden use of ammonia, but that further development is needed including of expansion valve materials and development of suitable semihermetic compressors. The paper presents plots of the azeotropic composition of the R-717/E170 blend, vapor pressure of the azeotrope and its components, a pressure-enthalpy diagram for the azeotrope, and comparisons of the coefficient of performance (COP) of the blend and ammonia for typical evaporator and condenser temperatures. It also gives plots of the discharge temperature versus compression ratio and condensing temperature.

H. Lippold and R. Heide (Institut für Luft- und Kältetechnik Dresden, ILK, Germany), **Der Einsatz von Kältemittelgemischen unter dem Aspekt der Verbesserung der Öllöslichkeit** [The Use of Refrigerant Blends for the Purpose of Improving Lubricant Solubility], *Bericht über die Kälte-Klima-Tagung* [Proceedings of the Refrigeration and Air-Conditioning Conference], Deutscher Kälte- und Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, 20:, 1993 (in German, rdb9851)

examination of blends of R-717 (ammonia) with amines to improve miscibility with compressor oils

K. Maczek, K. Wojtas, and J. Müller (Technical University of Cracow, Poland), **CO_2 - An Old Refrigerant,** *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 128-135, 1997 (8 pages with 8 figures and 4 tables, RDB9321)

presents a study of zeotropic mixtures as replacements for R-22; compares the coefficient of performance (COP) of R-22, R-134a, R-32/134a (29/71), R-744/32/134a (7/31/62), and R-744/134a/236fa (6/76/18); summarizes cycle analyses and laboratory tests in a water-to-water refrigeration (heat pump) circuit to measure heating and cooling performance; concludes that use of R-744 (carbon dioxide) as a blend component increases the capacity and, when combined with a low-pressure component such as R-134a offers promise as an R-22 replacement; also concludes that R-744/134a/236fa (6/76/18) can be used as a refrigerant in high-temperature heat pumps and that 67% higher efficiency results with counterflow heat exchange to take advantage of the glide

K. Maczek, J. Müller, K. Wojtas (Technical University of Cracow, Poland), and P. A. Domanski (National Institute of Standards and Technology, NIST), **Ternary Zeotropic Mixture with CO_2 Component for R-22 Heat Pump Application,** *CLIMA 2000 '97*, Brussels, Belgium, 1997 (9 pages with 4 figures and 7 tables, RDB9322)

summarizes tests of R-32/134a (29/71) and R-744/32/134a (7/31/62) as well as R-22 for reference in a laboratory test rig for a water-to-water heat pump; presents results for both drop-in and constant-capacity comparisons and compares them to performance simulations using CYCLE-11 (see RDB3448); discusses use of blends containing R-744 (carbon dioxide) as a component; concludes that the ternary zeotrope R-744/32/134a (7/31/62) yielded increases in both capacity and efficiency, but that it is suitable for drop in use only at low temperatures due to excessive condensing pressures; notes that the experimental coefficient of performance (COP) for this blend with counter-flow heat exchangers increased the heating mode COP by nearly 10% compared to R-22

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H. Madsbøll and G. Mindsen (Dansk Teknologisk Institut, DTI, Denmark), **A 2 MW Industrial Chiller Using Water as Refrigerant. Principles and Operational Experiences,** *Proceedings of the IIR Conference on Applications for Natural Refrigerants* (Århus, Denmark, 3-6 September 1996), International Institute of Refrigeration (IIR), Paris, France, 567-575, September 1996 (9 pages, rdb9335)

R-718 (water)

M. O. McLinden and D. A. Didion (National Institute of Standards and Technology, NIST), **Quest for Alternatives** (561-RP), *ASHRAE Journal*, 29(12):32-36, 38, 40, and 42, December 1987; republished in ASHRAE Special Publication, *CFCs: Time of Transition*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 69-78, 1989 (8/10 pages with 9 figures and 1 table, RDB2259)

This article reviews the criteria required of refrigerants and the reasons chlorofluorocarbons (CFCs) were originally investigated. A systematic examination, based on molecular structure, reveals a range of compounds that should be environmentally acceptable and still retain desired attributes. 860 compounds were screened, resulting in 51 fluids warranting further examination. The article notes that the number of compounds from which to choose alternatives is limited; the chlorofluorocarbon family - including fluorocarbons and hydrocarbons - remains the clear choice by virtue of stability, thermodynamic properties, health and safety characteristics, and familiarity. Some compromise with traditional criteria (e.g., capacity, flammability, and efficiency) will be needed. Present refrigerants resulted from more than 30 years of research and development. Careful scientific and technological planning are required to effect a significant change, and to avoid a new solution that introduces more problems than it solves.

P. Nekså (SINTEF Energy Research, Norway) **CO_2 Heat Pump Systems**, *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, presentations tab 18, 1999 (10 pages with 8 figures, RDB9835)

R-744 (carbon dioxide)

P. Nekså, G. R. Zakeri, R. Aarlien (SINTEF Energy Research, Norway), and A. Jakobsen (Norgest Tekniska Högskole, NTH, Norway), **Carbon Dioxide as Working Fluid in Air-Conditioning and Heat Pump Systems**, *The Earth Technologies Forum* (proceedings, Washington, DC, 26-28 October 1998), Alliance for Responsible Atmospheric Policy, Arlington, VA, 215-224, October 1998 (10 pages with 7 figures and 1 table, RDB8B18)

examination of R-744 (carbon dioxide) in transcritical cycles for air-conditioning and heat pump applications; theoretical and experimental findings for dual-mode (heating and cooling) heat pumps; heat pump water heaters (HPWH), and air- and water-cooled chillers; comparisons to R-22 and R-134a

P. Nekså and H. Rekstad (Norwegian University of Science and Technology, NTNU, Norway), **CO_2 Heat Pump Prototype Systems - Experimental Results,** *CO_2 Technology in Refrigeration, Heat Pump, and Air-Conditioning Systems* (proceedings of the IEA-HPC/IIR Workshop, Trondheim, Norway, 13-14 May 1997), International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, and the International Institute of Refrigeration (IIR), Paris, France, 1997 (rdb9239)

R-744 (carbon dioxide)

P. Nekså (Norgest Tekniska Högskole, NTH, Norway), **Transcritical Vapor Compression Heat Pumps**, *New Applications of Natural Working Fluids in Refrigeration and Air Conditioning* (proceedings of the meeting of IIR Commission B2, Hannover, Germany, 10-13 May 1994), International Institute of Refrigeration (IIR), Paris, France, 395-404, 1994 (10 pages, rdb9238)

R-744 (carbon dioxide)

N. Okaza, M. Funakura, and Y. Yoshida (Matsushita Electric Industrial Company, Limited, Japan), **Evaluation of New Composition of R407-Series for Air Conditioners**, *Proceedings of the Oji International Seminar* (Tomakomai, Hokkaido, Japan, 16-19 September 1997), Japan Society for the Promotion of Science and the Fujiwara Foundation of Science, Japan, 207-212, September 1997 (6 pages with 7 figures and 2 tables, available from JMC as RDB8201)

examines R-407E as a replacement for R-22: indicates that R-407C was formulated in light of revised flammability test methods to offer higher efficiency and lower global warming potential (GWP) than R-407C and lower discharge pressures than R-410A while maintaining similar pressure to R-22 and nonflammability; compares the capacities, coefficients of performance (COP), and discharge pressures of a range of R-32/125/134a formulations including 28/17/55, 30/18/52, 30/22/50, 30/0/70, 30/10/60, 25/20/55, 25/15/60 (R-407E), and 25/10/65; presents tests of R-407E in a 2.8 kW (0.8 ton) residential, split-system, room air conditioner; examines a cycle modification to incorporate a liquid-liquid heat exchanger to improve efficiency with the blend; concludes that R-407E offers higher COP improvement than expected from theoretical cycle analyses due to better heat transfer and lower suction pressure losses, that R-407E offers lower GWP and discharge pressure but higher COP compared to R-407C, and that incorporation of the liquid-liquid heat exchanger improves the cooling COP with R-407E by 5-6% over R-407C in a conventional cycle

J. Paul (Integral Energietechnik GmbH, Germany), **District Cooling with 'Water as Refrigerant' Combined with Energy Storage Systems,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 82-92, 1998 (11 pages with 9 figures and 7 tables, RDB9205)

discusses use of R-718 (water) as a refrigerant in large, district cooling systems: outlines a comparison to absorption-cycle chillers; describes approaches employing engine drives and ice storage; concludes that use of water as a refrigerant couples with thermal storage is economic for large systems

J. Paul (Integral Energietechnik GmbH, Germany), **Water as Refrigerant**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:955-960, 1995 (6 pages with 4 figures and 3 tables, rdb7934)

use of R-718 (water) as a refrigerant with illustrations for of a single-stage ice machine serving a mine and a two stage system using ammonia-water absorption for the second stage; comparison coefficients of performance (COPs) for R-718 and "conventional" refrigerants

S. F. Pearson (Star Refrigeration Limited, UK), **Ammonia Refrigeration Systems**, *ASHRAE Journal,* 41(3):24-26 and 28-29, March 1999 (5 pages with 3 figures, RDB9303)

discusses approaches to improve efficiency and safety of systems using R-717 (ammonia) with emphasis on low-charge systems designed to overfeed the evaporator without the use of pumps (identified as "low-pressure receiver", LPR, systems); briefly discusses lubricants noting that polyalkylene glycol (PAG) oils are miscible with ammonia, but are hygroscopic; mentions enhanced oil control with hydro-cracked and polyalphaolefin (PAO) lubricants; outlines considerations for defrost systems and concludes that the reversed-cycle defrost has advantages when properly controlled with time and demand initiation and pressure termination; briefly discusses applications involving ammonia thermosyphon systems for water chilling, low-charge systems, R-744 (carbon dioxide) cascaded with ammonia, and LPR systems for cold storage

J. Pettersen and R. Aarlien (SINTEF Energy Research, Norway), **Progress in CO_2 Vapour-Compression Systems,** *Proceedings of the Oji International Seminar* (Tomakomai, Hokkaido, Japan, 16-19 September 1997), Japan Society for the Promotion of Science and the Fujiwara Foundation of Science, Japan, 91-100, September 1997 (10 pages, rdb9244)

R-744 (carbon dioxide)

J. Pettersen, R. Aarlien, P. Nekså, G. Skaugen, and K. Aflekt (SINTEF Energy Research, Norway), **A Comparative Evaluation of CO_2 and R22 Residential Air-Conditioning Systems in a Japanese Climate**, *CO_2 Technology in Refrigeration, Heat Pump, and Air-Conditioning Systems* (proceedings of the IEA-HPC/IIR Workshop, Trondheim, Norway, 13-14 May 1997), International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, and the International Institute of Refrigeration (IIR), Paris, France, 1997 (rdb9241)

use of R-744 (carbon dioxide) in unitary air conditioners

J. W. Pillis (Frick Company), **Expanding Ammonia Usage in Air Conditioning**, *R-22 and R-502 Alternatives* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 19-20 August 1993), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 103-107, 1994 (5 pages with 3 figures and 1 table, RDB4525)

This paper presents tradeoffs for R-717 (ammonia) use in systems of different sizes. The author identifies good efficiency, high heat transfer coefficients, zero ozone depletion and global warming potentials (ODP and GWP), and low cost as positive aspects. He also cites favorable piping sizes tolerance to water contamination, near insolubility in mineral oils, and ammonia's self-alarming smell to warn of leaks. Toxicity, flammability in the range of 16-27% concentration in air, and incompatibility with copper are cited as negative aspects. A figure shows the efficiencies of R-12, R-22, R-134a, and R-502 relative to that of ammonia for -40 to 4 °C (-40 to 40 °F) assuming isentropic compression. The paper indicates that ammonia probably is not competitive in small refrigeration and air-conditioning systems based on incompatibility with copper, use of which results in systems that are simple to fabricate, are virtually leak free, and offer simple methods for field repairs. The pa-

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per discusses design changes required for oil return, need to develop low-cost motors that are compatible with ammonia, and consequences of high discharge temperatures with air-cooled condensing. Two plots show the discharge temperatures of R-22, R-134a, and ammonia at 55 °C and 130 °F as functions of evaporating temperature. The paper notes that ammonia is widely used in large refrigeration systems, notably in industrial applications, based on favorable thermodynamic characteristics and low costs. It also notes that the zeotropic alternatives to R-22 would be a major concern in these applications due to their size, opportunities for leaks, potential for fractionation, and consequent servicing complexity. R-134a is not a good choice due to poor low-temperature efficiency, and the pressures associated with R-32 would necessitate new compressor designs. With R-22 phaseout, ammonia is suggested as the best choice. The paper discusses its advantages for these systems and notes that typical use of open drives, steel pipe for strength and durability, and evaporative condensers overcome the concerns cited for small systems. With zeotropes excluded for chillers in large air-conditioning systems, due to wide use of flooded evaporators and service considerations, ammonia and azeotropes are suggested as alternatives. The paper describes requirements for greater ammonia use including development of cost-competitive, enhanced heat exchangers fabricated with steel, aluminum, or other materials. Based on part-load efficiency, screw or reciprocating-piston compressors would be favored over multistage centrifugal compressors, needed for the high pressure differentials. Two installations of large ammonia chillers are described. Medium-sized chillers as cited as a market segment where ammonia use could increase. Several new packaged chillers, using ammonia, are cited as examples. The paper then discusses impediments to broader use of ammonia, among them toxicity and flammability. Several building code requirements are discussed and contrasted with a table showing the effects of exposure to increasing concentrations of ammonia. Some of the code requirements are suggested to be arbitrarily stringent. The author concludes that ammonia is not the answer for all or even a majority of air-conditioning systems, but that it is a good solution in many installations. He suggests caution to avoid over-regulation of ammonia use and a need to develop codes and standards that provide safe systems, without unnecessary restrictions and cost requirements.

M. Saikawa and K. Hashimoto (Central Research Institute of Electric Power Industry, CRIEPI, Japan), **An Experimental Study on the Behavior of CO_2 Heat Pump Cycle,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 223-229, 1998 (7 pages with 7 figures and 1 table, RDB9216)

presents a cycle analysis for a heat pump using R-744 (carbon dioxide) in a transcritical cycle; describes a test loop, control issues, experimental results with adjusted compressor speed, and performance changes with varied source and sink temperatures; includes discussion by A. Jakobsen (Danmarks Tekniske Højskole, DTH, Denmark) and V. W. Goldschmidt (Purdue University, USA)

M. Saikawa (Central Research Institute of Electric Power Industry, CRIEPI, Japan), K. Hashimoto (CRIEPI), H. Hasegawa (CRIEPI), T. Iwatsubo (CRIEPI), and J. Straub (Technische Universität München, TUM, Germany), **A Basic Study on CO_2 Heat Pumps Especially for Hot Tap Water Supply**, *CO_2 Technology in Refrigeration, Heat Pump, and Air-Conditioning Systems* (proceedings of the IEA-HPC/IIR workshop, Trondheim, Norway, 13-14 May 1997), International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, and the International Institute of Refrigeration (IIR), Paris, France, 1997 (5 pages with 14 figures and 2 tables, RDB9873)

presents a cycle analysis for a heat pump water heater (HPWH) using R-744 (carbon dioxide) in a transcritical cycle; discusses the characteristics and control methods for this cycle; documents experiments with both manual and automatic control of a test system; concludes that operation of the R-744 system is not very different from conventional vapor-compression systems even though the cycle has unique characteristics; indicates that the R-744 HPWH achieves a higher coefficient of performance (COP) than an R-22 system based on calculated performance

A. Sekiya (National Institute of Materials and Chemical Research, NIMC, Japan) and S. Misaki (Research Institute of Innovative Technology for the Earth, RITE, Japan), **Development of Hydrofluoroethers as Alternative Refrigerants and Other Applications,** *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 26-33, November 1997 (8 pages with 1 figure and 7 tables, RDB8323)

systematic examination of candidate hydrofluoroether (HFE) refrigerants: tabular comparison of the normal boiling point, critical temperature and pressure, liquid density, specific heat ratio, atmospheric lifetime, global warming potential (GWP), and ozone depletion potential of R-11, R-123, R-245fa, R-E347mcc3 (identified in the paper as "HFE-347mcc"), and R-E347mmy1 ("HFE-347mmy"), of R-114, R-E227ea1 ("HFE-227me"), and R-E245cb1 ("HFE-245mc"), of R-12 and R-134a, and of R-22, R-407C, and R-410A; thermal stability of R-E245cb1 with lubricants and metals (aluminum, copper, and steel); comparison of the electric resistance and dielectric constant of R-E245cb1 to those of R-22, R-113, and R-134a; cycle performance comparisons; and vapor thermal conductivity of candidate foam blowing agents, namely R-E134, R-E227ea1, R-E245ca2, R-E245cb1, R-245fa, R-E245fa1, R-E329mcc2, R-E338mmz1, R-E347mcc3, R-E347mcf1, R-E347mfc2, R-E347mmy1, R-E254cb1, and R-E356mmz1

G. Skaugen (Norgest Tekniska Högskole, NTH, Norway) and M. C. Svensson (Sør-Trøndelag College, Norway), **Dynamic Modeling and Simulation of a Transcritical CO_2 Heat Pump Unit,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 230-239, 1998 (10 pages with 8 figures, RDB9217)

describes a model for simulation of heat pumps using R-744 (carbon dioxide) in a transcritical cycle; indicates good qualitative agreement between predicted and measured performance; includes discussion by P. A. Domanski (National Institute of Standards and Technology, NIST, USA) and V. W. Goldschmidt (Purdue University, USA)

W. F. Stoecker (University of Illinois at Urbana-Champaign), **Comparison of Ammonia with Other Refrigerants for District Cooling Plant Chillers**, paper NO-94-15-2, *Transactions* (Winter Meeting, New Orleans, LA, January 1994), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 100(1):1126-1135, 1994 (10 pages, RDB9312)

R-717 (ammonia)

S. G. Sundaresan (Copeland Corporation), **Industry Experiences with HFC Refrigerants - Contaminant Control: Key to Hermetic Systems Integrity**, *Proceedings* (Session 1997-1998), The Institute of Refrigeration, London, UK, 2-1 - 2-6, 1997 (6 pages with 2 figures and 3 tables, RDB8344)

discusses experience with hydrofluorocarbon (HFC) refrigerants and the need for contaminant control to insure proper system performance and to avoid malfunctioning of expansion devices; focuses on R-134a with polyolesters (POE) lubricants in appliances; on R-134a, R-404A, and R-507A with POEs in commercial refrigeration; and on R-407A and R-410A with mixed acid POE (MA-POE), hydrolytically stable (hindered acid) POE (HSPOE), and polyvinyl ether (PVE) in air conditioners and heat pumps

J. Süß and H. H. Kruse (Universität Hannover, Germany), **Heat Transfer Phenomena Inside the Cylinder of CO_2-Compressors and the Influence on their Efficiency,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 260-269, 1998 (10 pages with 9 figures, RDB9221)

summarizes theoretical and experimental investigations of heat transfer inside the compression cylinder of a reciprocating piston compressor using R-744 (carbon dioxide); contrasts the heat transfer impact for this refrigerant to that of others; describes the measurement method; estimates the impacts on efficiency; compares the influences of compressor types; concludes that the overall influence of heat transfer phenomena is negligible for modern CO_2 compressors even though high at specific points in the process; includes discussion by M. S. Kim (Seoul National University, Korea), B. E. Fagerli (Norwegian University of Science and Technology, NTNU, Norway), H. Quack (Technische Universität Dresden, Germany), and V. W. Goldschmidt (Purdue University, USA)

J. Süß and H. H. Kruse (Universität Hannover, Germany), **Design Criteria of CO_2-Compressors for Vapor-Compression Cycles**, *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 139-147, 1997 (9 pages with 9 figures, RDB9323)

reviews the characteristics of different compressor types to identify those suitable for use with R-744 (carbon dioxide); notes that this refrigerant involves a low pressure ratio even though the working pressure and pressure lift are high; describes modifications to the valves, cylinder seals, cylinder geometry, and piston rods for an open-drive reciprocating-piston compressor investigated to achieve high volumetric and energetic efficiency

J. Süß and H. H. Kruse, **Einfluß von Leckage auf die Efficienz von Verdichtern für Kohlendioxid** [Influence of Leakage on the Efficiency of Compressors for Carbon Dioxide], *Ki Luft- und Kälte-*

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technik, 33(4):173-176, April 1997 (4 pages in German, rdb9245)

use of R-744 (carbon dioxide) as a refrigerant; consequences of high pressure on internal leakage in compressors and resulting impact on performance

J. Süß and H. H. Kruse (Universität Hannover, Germany), **Untersuchungen zur Effizienz des Arbeitsprozesses von Verdichtern für Kohlendioxid** [Investigation of the Efficiency of the Work Processes Compressors for Carbon Dioxide], *DKV Jahrestagung* [Proceedings of the DKV Annual Meeting] (Leipzig, Germany), Deutscher Kälte- und Klimatechnischer Verein (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Germany, (II.2):, 1996 (in German, RDB9326)

use of R-744 (carbon dioxide) as a refrigerant

T. Tiedemann, M. Burke, and H. H. Kruse (Universität Hannover, Germany), **Recent Developments to Extend the Use of Ammonia**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 389-395, July 1996 (7 pages with 7 figures, RDB6C12)

R-717, experimental results for a semihermetic compressor with a resistant lacquer to protect the motor windings, dry-expansion evaporation using plate heat exchangers, oil return using soluble polyalkylene glycol (PAG) oils described as "an equivalent of ethylene oxide and propylene oxide compounds," and aluminum piping with new solders; performance comparisons to R-22 suggesting a potential for improvement by approximately 12%

D. W. Treadwell (Lennox Industries Incorporated), **Performance Cost and Safety Requirements of Employing R290 (Propane) in Unitary Air Conditioning Equipment**, paper 2.6, *Proceedings of the International Symposium on R22 & R502 Alternative Refrigerants '94 - Performance Evaluations and Commercialization Issues for Air Conditioning and Refrigeration Equipment* (Kobe, Japan, 8-9 December 1994), Japan Refrigeration and Air-Conditioning Industry Association (JRAIA), Tokyo, Japan, 42-45, December 1994 (4 pages with 1 table, RDB-5409)

This paper discusses the performance, cost, and safety implications for use of R-290 (propane) in an 8.8 kW (2½ ton) single-package, air-cooled, unitary air conditioner. Test results are tabulated for R-22 and propane, the latter after replacement of the compressor with one having an 18% larger displacement. The table compares the capacity, input power, resultant energy efficiency ratio (EER), refrigerant charge amount, suction and discharge temperatures and pressures, and liquid temperatures at standard rating conditions. The paper notes that the capacity and efficiency are higher with propane and the larger compressor, while the discharge temperature and pressure are favorably lower. It notes that propane is more compatible than R-22 with most materials used, is readily available, is approximately 1/6th the cost of R-22, is non-toxic, has no ozone depletion potential (ODP), and near zero global warming potential (GWP) - approximately 0.2% that of R-22. Also, the charge size would be less than half. The paper then summarizes the findings of a risk assessment for propane use in a 12.3 kW (3½ ton) air conditioner, based on an independent analysis and a product evaluation by an independent test laboratory. They were performed by Arthur D. Little (ADL) and Underwriters Laboratory (UL), respectively. Modifications to isolate the refrigerant in the evaluation unit are outlined, as are further requirements identified by the independent evaluation. A subsequent cost estimate by the manufacturer found that these safety requirements would increase the product cost by 30% over one with R-22. The increment was estimated to be even higher for a unitary, split-system air conditioner. The paper concludes that while propane was deemed to be an excellent refrigerant, the cost to use it would far exceed that to switch to a nonflammable, hydrofluorocarbon (HFC) blend.

J. Wertenbach and R. Caesar (Daimler-Benz AG, Germany), **An Environmental Evaluation of an Automobile Air Conditioning System with CO_2 versus HFC-134a as Refrigerant**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 324-334, 1998 (11 pages with 9 figures and 7 tables, RDB9230)

compares the total equivalent warming impacts (TEWI) of mobile air conditioning systems (MACS) using R-134a and R-744 (carbon dioxide) including the impacts of increased fuel use to transport the heavier carbon dioxide system; concludes that carbon dioxide may lower TEWI for any of four scenarios, namely for the climates of Frankfurt Germany and Miami FL USA each for optimistic and pessimistic scenarios of refrigerant losses; notes that efficiency improvements are possible over current systems for both refrigerants; also notes that the environmental benefit from carbon dioxide use can be achieved without reducing occupant comfort, but that further verification of the safety, dynamic performance, system weight reduction, costs, and reliability are needed to determine its suitability; includes discussion by L. Asteberg (Ingenjörfirman Lennart Asteberg AB, Sweden) and D. C. Zeitlow (Visteon, USA)

J. Wertenbach and F. Kaul (Daimler-Benz AG, Germany), **High-Pressure Refrigeration System with CO_2 in Automobile Air Conditioning**, *CO_2 Technology in Refrigeration, Heat Pump, and Air-Conditioning Systems* (proceedings of the IEA-HPC/IIR Workshop, Trondheim, Norway, 13-14 May 1997), International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, and the International Institute of Refrigeration (IIR), Paris, France, 1997 (RDB9227)

summarizes results of the Refrigeration and Automotive Climate Systems under Environmental Aspects (RACE) project, a collaborative effort by European automobile manufacturers and suppliers to investigate use of R-744 (carbon dioxide) for mobile air conditioning systems (MACS): the three-year effort under the auspices of the European Council for Automotive Research and Development (EUCAR) was sponsored by the European Community; the paper describes the transcritical cycle selected and component and system performance analyses

Y. Yoshida, M. Funakura, N. Okaza, and M. Matsuo (Matsushita Electric Industrial Company, Limited, Japan), **Residential Use Air Conditioner for Advanced COP: Acceptability of HFC-32/Hydrocarbon Mixtures,** *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlagsund Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, presentations tab 16, 1999 (8 pages with 7 figures and 5 tables, RDB9834)

examines alternatives to R-410A to replace R-22 in residential air conditioners, to achieve higher performance with a lower refrigerant global warming potential (GWP): notes that blends of R-32 with R-290 (propane), R-600 (n-butane), and R-600a (isobutane) form azeotropes at compositions of approximately R-32/290 (75/25), R-32/600 (95/5), and R-32/600a (90/10), respectively; notes that the High Pressure Gas Safety Law of Japan considers a refrigerant to be nonflammable if its lower flammability limit (LFL) exceeds 10% v/v and the difference between the upper flammability limit (UFL) and the LFL is less than 20% v/v; indicates that R-32, R-32/600, and R-32/600a qualify as long as the hydrocarbon component does not exceed approximately 5% by mass; presents flammability test data for R-32/600 for blends containing up to 10% v/v R-600 according to a new test method ("34p") being considered for ASHRAE Standard 34; indicates that R-32/600 and R-32/600a would fall in flammability class 2 by this method as long as the hydrocarbon (HC) components do not exceed 26% m/m; provides cycle comparisons of R-32, R-410A, R-32/600 (95/5), and R-32/600a (95/5) suggesting that the HC blends reduce the discharge temperature of R-32 and improve the coefficient of performance (COP) by lowering the required compression ratio; summarizes laboratory tests of split-system heat pumps with a single and multiple indoor units with R-32, R-410A, R-32/600 (90/10), R-32/600 (95/5), R-32/600a (90/10), and R-32/600a (95/5); indicates improvements of 7% in cooling COP and 2% in heating COP for R-32 compared to R-410A and 7 and 2-3% for the R-32/HC blends; notes that these blends lower both the discharge temperature compared to neat R-32 and the GWP compared to either R-32 or R-410A; the blends also enable use of mineral oil lubricants and achieved acceptable oil return; concludes that R-32/600 with 5-10% m/m R-600 was deemed "useful"

X-Y. Zhao, L. Shi, L-Z. Han, and M-S. Zhu (Tsinghua University, China), **Update on Mixture THR02 as a Long-Term Alternative to CFC-12 and HFC-134a**, *Proceedings of the International Conference on Ozone Protection Technologies* (Baltimore, MD, 12-13 November 1997), Alliance for Responsible Atmospheric Policy, Arlington, VA, 74-81, November 1997 (8 pages with 5 figures and 10 tables, RDB8329)

THR02 blend [R-290/152a/13I1]: calculated performance comparisons to R-134a in a refrigerator and in and automobile air conditioner; miscibility with mineral oil (MO), alkylbenzene (AB), and polyolester (POE) lubricants; materials compatibility findings for metals (copper, and aluminum), polyethylene terephthalate (PET), polybutylene terephthalate (PBT), and unidentified enameled magnet wire, tie cord, gasket material, and plastic pipe; analyses of composition shifts and leakage; concludes that THR02 is promising, can be used with MO lubricants, offers performance that equals or exceeds those of R-12 and R-134a, is compatible with common materials, and has run without problem for two years in a retrofit test

Alternatives to Chlorofluorocarbons, bulletin AG-1 (document H-16411-2), DuPont Chemicals, Wilmington, DE, January 1992 (8 pages with 3 figures and 3 tables, available from JMC as RDB4511)

This bulletin discusses nine alternative refrigerants including five hydrochlorofluorocarbons (HCFCs) - R-22, R-123, R-124, R-141b, and R-142b - and six hydrofluorocarbons (HFCs) – R-23, R-32, R-125, R-134a, R-143a, and R-152a. It

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briefly outlines testing for safety and performance and provides a figure contrasting the ozone depletion (ODP) and halocarbon global warming potentials (HGWP) of these refrigerants. A second figure shows their relative photochemical reactivity, or relative contribution to ground-level smog. Tables summarize the range of applications - including as refrigerants, blowing agents, and for other uses - of these fluids and their physical properties. The tabulated data include chemical name and formula, molecular weight, boiling and freezing points, critical parameters (temperature, pressure, specific volume, and density), heat of vaporization, flammability limits in air, ODP, halocarbon GWP (HGWP), Toxic Substances Control Act (TSCA) inventory status, and recommended chronic exposure limit for toxicity. The density, specific heat, vapor pressure, thermal conductivity, viscosity, and solubility in water are given for 25 °C (77 °F). A plot shows the vapor pressure relations to temperature; R-11, R-12, R-113, and R-114, R-500, R-502 also are shown for reference.

Hydrocarbons in Refrigeration Systems, Association of European Compressor Manufacturers (ASERCOM), June 1997 (rdb9849)

IDENTIFICATION

Center for Global Environmental Technologies (CGET), **Halocarb© Computer Program and Halocarbon Nomenclature,** Technical Update Series CGET3, New Mexico Engineering Research Institute (NMERI), Albuquerque, NM, 22 March 1994 (computer disk with software and 8 page documentation with 3 tables, limited copies available from JMC as RDB4674)

This software determines the International Union of Pure and Applied Chemistry (IUPAC) name, halon number, and molecular weight for halocarbons from the structural chemical formula. It does not handle unsaturated, cyclic, or branched-chain compounds. The program runs on DOS-based computers. The documentation reviews the IUPAC nomenclature rules, ASHRAE Standard 34 numbering system, composition-designating prefixes, and halon numbering system. Tables summarize the composition-designating prefixes and conventions for isomer suffixes. Some of the numbering and prefix conventions presented are extensions to those adopted in Standard 34.

International Union of Pure and Applied Chemistry (IUPAC), **Nomenclature of Organic Chemistry, Sections A, B, C, D, E, F, and H,** prepared by J. Rigaudy and S. P. Klesney, Pergamon Press Incorporated, New York, NY, 1979 (RDB4202)

This document presents a system of uniform nomenclature to identify organic chemicals, including most common refrigerants. The rules were formulated and adopted by the IUPAC Commission on the Nomenclature of Organic Chemistry. The sections (A-F and H) incorporated in this publication cover hydrocarbons; fundamental heterocyclic systems; characteristic groups containing carbon, hydrogen, oxygen, nitrogen, halogens, sulfur, selenium, and/or tellurium; organic compounds containing elements that are not exclusively carbon, hydrogen, oxygen, nitrogen, halogens, sulfur, selenium, and tellurium; stereochemistry; general principles for the naming of natural products and related compounds; and isotopically modified compounds. The rules respond to a stated belief "that differences in nomenclature frequently hinder the accurate and intelligible conveyance of information from one chemist to another, so tending to hamper understanding and progress." [An attempt is being made to conform to the definitive IUPAC rules in citing chemical names in the Refrigerant Database, though application of these rules is sometimes challenging.]

Assignment of Refrigerant Container Colors, ARI Guideline N-1995, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1995 (12 pages, with 1 table, available from ARI for $10.00 for members and $20.00 for nonmembers, RDB6601)

This guideline sets color standards for containers for existing, new, and reclaimed refrigerants. It further provides a means by which ARI can assign colors as new refrigerants are introduced, and maintains a record of those assigned and available. The guideline also recommends a container color (light green grey) for refrigerants that are not produced in sufficient quantities to qualify for individual colors. While color coding is not intended as a substitute for reading cylinder labels and markings, the guideline facilitates distinction among refrigerant containers by content. Four groups are identified, namely those for liquids at 20 °C (68 °F) normally packaged in drums, low-pressure fluids, high pressure fluids, and flammable (red band) refrigerants or mixtures. A table summarizes color assignments and corresponding color matching data. Refrigerants with assigned colors include R-11 (orange), R-12 (white), R-13 (light blue, sky), R-13B1 (pinkish-red, coral), R-14 (yellow-brown, mustard), R-22 (light green), R-23 (light blue grey), R-113 (dark purple, violet), R-114 (dark blue, navy), R-116 (dark grey, battleship), R-123 (light blue grey), R-124 (dep green, DOT green), R-125 (medium brown, tan), R-134a (light blue, sky), R-401A (pinkish red, coral), R-401B (yellow-brown, mustard), R-401C (blue-green, aqua), R-402A (light brown, sand), R-402B (green-brown, olive), R-404A (orange), R-407A (lime green), R-407B (cream), R-407C (medium brown, brown), R-408A (medium purple, purple), R-409A (medium brown, tan), R-410A (rose), R-410B (maroon), R-500 (yellow), R-502 (light purple, lavender), R-503 (blue-green, aqua), and R-507A (blue-green, teal).

ABSORPTION AND ADSORPTION

I. Borde, M. Jelinek, and N. C. Daltrophe (Ben-Gurion University of the Negev, Israel), **Working Substances for Absorption Heat Pumps Based on R32**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:80-87, 1995 (8 pages with 9 figures and 8 tables, rdb7728)

thermodynamic and transport properties of R-32/DMAC (N,N'-dimethylacetimide); performance comparison for use of R-22, R-32, R-124, and R-134a as the refrigerant with DMAC as the absorbent in a single stage absorption heat pump that uses a jet ejector as a mixer and pre-absorber; comparison shows that R-32/DMAC has the highest coefficient of performance (COP), but requires a circulation ratio and is valid only at generator temperatures exceeding 115 °C (239 °F); R-22/DMAC gave the best overall performance

I. Borde, M. Jelinek, and N. C. Daltrophe (Ben-Gurion University of the Negev, Israel), **Absorption System Based on the Refrigerant R134a,** *International Journal of Refrigeration*, 18(6):387-394 July 1995 (8 pages, rdb8918)

examines use of R-134a as a refrigerant in absorption-cycle systems with different organic absorbents: discusses use of dimethylether tetraethyleneglycol (DMETEG), N-methyl epsilon-caprolactam (MCL), and dimethylethyleneurea (DMEU) as candidate absorbents; presents calculation procedures for the working pair R-134a and DMETEG; presents temperature-pressure-concentration curves based on vapor-liquid equilibria (VLE) measurements; also presents enthalpy-concentration diagrams calculated using excess thermodynamic properties of the mixture; outlines measurements of the density and viscosity of the working fluids; summarizes thermal stability tests of R-134a with DMETEG, which found no changes in either of the phases; compares the performances of the investigated working fluids based on a computerized simulation program for a single-stage absorption cycle using a jet ejector as a mixer and preabsorber; the coefficient of performance (COP) for the three combinations were similar (R134a-DMEU reached 0.49, R134a-MCL 0.47, and R134a-DMETEG 0.46), but the value of the circulation ratio for R134a-DMTEG was lower than for the other two pairs; recommends R-134a-DMETEG as the best of the three candidate working pairs

L. W. Burgett, M. D. Byars, and K. J. Schultz (The Trane Company), **Absorption Systems: The Future, More Than a Niche?**, *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 66-79, 1997 (14 pages with 8 figure, RDB7B08)

reviews the historical development and penetration of absorption refrigeration; contrasts differences in driving factors and acceptance among Japan, the United States, and other countries; outlines the development status of triple-effect absorption chillers, other advanced designs, heat pumps, heat transformers, and other heat-activated technologies; paper notes that efficiency improvements offered by triple-effect designs are offset by relatively large increases in first cost that will limit its competitive advantage; concludes that while absorption use exceeds a niche classification in some areas of the world, it does not in the United States; the paper indicates that technology breakthroughs are unlikely with mature technologies and that there is no evidence to project a significant change

D. Clodic and C. Ciucasu (École des Mines de Paris, France), **An Optimized Configuration for the Triple-Effect Absorption Cycle**, *Proceedings of the 1996 International Refrigeration Conference at Purdue* (23-26 July 1996), edited by J. E. Braun and E. A. Groll, Purdue University, West Lafayette, IN, 343-348, July 1996 (6 pages with 4 figures, RDB6926)

R-717/718 (ammonia/water), performance calculation, cycle optimization

G. Grossman (Technion, Israel), M. Wilk, and R. C. DeVault (Oak Ridge National Laboratory, ORNL, USA), **Simulation and Performance Analysis of Triple-Effect Absorption Cycles,** *Transactions,* American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 100, 1994 (rdb6927)

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performance calculation, cycle optimization

D. Hisajima, R. Sakiyama, and A. Nishiguchi (Hitachi Limited, Japan), **Evaluation of Absorbents for an Absorption Heat Pump Using Natural Organic Working Fluids (Eco-Energy City Project)**, *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 11, 1999 (10 pages with 10 figures and 8 tables, RDB9843)

outlines methods to estimate the vapor-liquid equilibrium (VLE) properties considering intermolecular forces for working fluids for absorption heat pumps; presents measured and calculated data on natural organic substances considered as candidate refrigerants and absorbents; tabulates promising candidates for use with R-E170 (dimethyl ether) and R-600a (isobutane); concludes that the Predict-Soave-Redlich-Kwong (PSRK, sometimes referred to as the Predict-Redlich-Kwong-Soave, PRKS) equation of state (EOS) gives a better estimation for hydrocarbons than other methods; also concludes that alkanes and alkenes that have five or six carbons (C5 or C6), such as cyclopentane and cyclopentene are good absorbents for R-600a while molecules that have an oxide double bond (=O), such as aldehyde, carboxylic acid, ketone, and ester, are likely to be good combinations with R-E170

S. Iyoki, Y. Kuriyama, H. Tanaka, and T. Uemura (Kansai University, Japan), **Performance Analyses of Absorption Refrigerating Machine and Heat Pump Using H_2O + LiCl + $LiNO_3$ System**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:1160-1167, 1995 (8 pages with 9 figures, rdb8306)

performance analyses for cooling and heating in an R-718 (water) / lithium chloride + lithium nitrate (2.8:1 by mole) system with comparisons to water / lithium bromide (LiBr) in single- and double effect cycles and variants

T. Kashiwagi (Tokyo University of A&T, Japan) and J-I. Yoon (National Fisheries University of Pusan, Korea), **The Effect of Additives in the Absorption and Regenerative Processes of Lithium Bromide-Water Refrigeration Cycles**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:329-336, 1995 (8 pages with 9 figures, rdb7822)

effect of additives such as n-octagonal to lithium bromide (LiBr) solutions: results show that regenerator heat transfer improves with higher pressure and lower concentrations; solution heat transfer is not significantly affected by addition of the n-octanol surfactant

M. Kojima and T. Kashiwagi (Tokyo University of A&T, Japan), **Mass Diffusivity Measurements for Ammonia-Vapour Absorption Processes,** *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:353-360, 1995 (8 pages with 6 figures, rdb7824)

experimental study of ammonia/salt and ammonia/water-salt systems: mass diffusivity of ammonia/salt absorbent solutions is lower than that of ammonia/water; use of surfactant additives

R. A. Macriss and T. S. Zawacki, **Absorption Fluids Data Survey 1989 Update**, report ORNL/Sub/84-47989/4, Oak Ridge National Laboratory, Oak Ridge, TN, 1989 (52 pages with 21 tables, available from NTIS, RDB1146)

This document updates the series of reports on absorption fluids and data, ORNL/Sub/84-47989/1,2,3, with data developed and published primarily between 1985-1988, and by citation of 44 additional references. Seventy-four worldwide publications containing data relating to properties of binary, ternary, and multicomponent absorption fluids are identified. The fluids discussed include combinations of 9 different refrigerant compounds, as well as 30 single, 7 binary, and 1 ternary absorbent compounds.

K. Murakami, H. Sato, and K. Watanabe (Keio University, Japan), **Dühring Charts and Enthalpy Concentration Charts for the LiBr/H_2O and LiCl/H_2O Solutions**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:428-435, 1995 (8 pages with 4 figures and 2 tables, RDB7842)

enthalpy-concentration charts as well as Dühring equations and charts for water/lithium bromide (H_2O/LiBr) and water/lithium chloride (H_2O/LiCl) solutions for use in absorption cycle equipment for 0-227 °C (32-441 °F) concentrations (weight fractions) of 0.30-0.75 for H_2O/LiBr and 0.10-0.50 for H_2O/LiCl

N. Nishiyama, K. Hujikura, and A. Shitara (Tokyo Gas Company, Japan), **Development of Absorption Heat Pump Using New Working Fluid**, *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25

August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:1213-1220, 1995 (8 pages with 7 figures and 2 tables, rdb8309)

examination of R-718 (water) / LiBr + LiI + LiCl + $LiNO_3$ (100:75:41:25 mole ratio, 1.00/1.16/-0.20/0.20 by mass): tests in a direct fired, switchable single- or double-effect absorption-cycle heat pump using treated sewage effluent as the heat source and sink tests showed a 5-10% increase in the coefficient of performance (COP) and higher output temperatures compared to R-718/LiBr

M. Nogues, M. Bourouis, D. Boer, and A. Caronas (Universität Rovira i Virgili, Spain), **Absorption-Compression Heat Pumps Using Methanol-TEGDME and Trifluoroethanol-TEGDME**, *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 197-204, 1997 (8 pages with 5 figures and 1 table, RDB9336)

examines use of the refrigerant-absorbent pairs methanol-teraethyleneglycol (TEGDME) and trifluoroethanol-TEGDME (TFE-TEGDME) in absorption-compression, industrial heat pumps using a desorber-absorber heat exchanger (DAHX); concludes that TFE-TEGDME warrants further study, but that cycle-performance with methanol-TEGDME was too low to make it suitable

Develop Improved Design Techniques for Aqueous LiBr Falling Film Absorption Through Application of an Innovative and Nonintrusive Temperature Measurement Technique, proposed research project 798-URP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, in planning (ASH-0798)

The project is being evaluated by ASHRAE Technical Committee 8.3, *Absorption and Heat-Operated Machines*. Further information is available from the ASHRAE Manager of Research (+1-404/636-8400).

Working Fluids and Transport Phenomena in Advanced Absorption Heat Pumps, report HPTC-30-2, edited by T. Saito, Heat Pump Technology Center of Japan, Tokyo, Japan, II, March 1990 (362 pages, RDB1148)

This report summarizes the findings of the International Energy Agency (IEA) research project on *Working Fluids and Transport Phenomena in Advanced Absorption Heat Pumps* (Annex XIV).

NOT-IN-KIND TECHNOLOGIES

P. Albring and G. Heinrich (Institut für Luft- und Kältetechnik Dresden, ILK, Germany), **Turbo Chiller with Water as a Refrigerant**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 93-103, 1998 (11 pages with no figures or tables, RDB9206)

describes development and tests of a compact, semihermetic, two-stage, axial turbocompressor for use of R-718 (water) as a refrigerant in capacities of 500-1000 kW (142-284 ton) at temperatures of 0-20 °C (32-68 °F); not-in-kind (NIK) technology

S. K. Fischer, J. J. Tomlinson, and P. J. Hughes (Oak Ridge National Laboratory, ORNL), **Energy and Global Warming Impacts of Not-in-Kind and Next Generation CFC and HCFC Alternatives**, Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) and U.S. Department of Energy (DOE), Washington, DC, 1994 (216 pages with 44 figures and 18 tables, limited copies available from JMC as RDB5509)

not-in-kind (NIK) technologies

G. Grazzini and M. D'Albero (Dipartimento di Energetica, Italy), **A Jet-Pump Inverse Cycle with Water Pumping Column**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 63-70, 1998 (8 pages with 6 figures and 1 table, RDB9203)

outlines a study to examine use of R-718 (water) as a refrigerant in a heat-driven, ejector cycle requiring no pump; describes tests of both single- and two-stage systems, the latter with a concentric ejector arrangement; concludes that the system is simple and reliable, but penalized by low efficiency; not-in-kind (NIK) technology; includes discussion by I. W. Eames (University of Nottingham, UK) and A. Ophir (Ide Technologies Limited, Israel)

M. Kauffeld and K. Gardø Christensen (Danish Technological Institute, DTI, Denmark), **Reefer 2000 - A New Energy-Efficient Reefer Container Using Carbon Dioxide as Refrigerant**, *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 399-408, 1998 (10 pages with 5 figures and 6 tables, RDB9246)

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examines R-134a, R-290 (propane), R-404A, R-600a (isobutane), R-717 (ammonia), R-729 (air), R-744 (carbon dioxide), and R-744A (nitrous oxide) as refrigerants to replace R-12 and R-22 in refrigerated cargo containers ("integrated reefer containers," IRC); excludes all but R-744 and R-744a based on global warming potential, toxicity, and/or flammability; concludes that R-744 and R-744A would yield almost identical thermodynamic performance and, therefore, favors R-744 for its lower global warming potential (GWP); summarizes simulations of a transcritical cycle using R-744 for cooling and freezing (medium and low temperature) duty; concludes that R-744 could replace R-134a, though the paper shows 18 and 22% higher coefficients of performance (COP) for R-134a based on the maximum obtainable performance for R-744 for unconstrained pressure in the gas cooler; notes that the R-744 system would require a smaller compressor (with the same size motor) and gas cooler (compared to the R-134a condenser); includes discussion by H. Quack (Technische Universität Dresden, Germany)

S. Lund and L. Søe (Danish Technological Institute, DTI, Denmark), **District Heating Assisted Ejector Cycle Refrigeration Plant for Process Cooling and Air-Condition**[ing] **Purposes,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 71-81, 1998 (11 pages with 12 figures, RDB9204)

describes planned tests of an ejector refrigeration system using R-718 (water) as the refrigerant: predicts an annual coefficient of performance (COP) of 1.38; calculates the economics of the concept and concludes that it would be economic at capacities exceeding 400 kW (114 ton); not-in-kind (NIK) technology; includes discussion by I. W. Eames (University of Nottingham, UK) and A. Koren (Ide Technologies Limited, Israel)

P. G. Lundqvist, **Stirling Cycle Heat Pumps and Refrigerators**, doctoral thesis ISRN KTH/REFR/R-93/9-SE (Department of Applied Thermodynamics and Refrigeration), Kungliga Tekniska Högskolan (KTH), Stockholm, Sweden, 1993 (rdb9334)

use of R-704 (helium) as a refrigerant

M. P. Maiya (Indian Institute of Technology, IIT), **Water Cooling by an Expanding Air Stream,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 104-113, 1998 (10 pages with 5 figures, RDB9207)

describes the concept and analyses of moist-air expansion cooling that combines an open, air-standard Brayton cycle with evaporative cooling (adiabatic saturation) to achieve a cooling effect in an isentropic expansion process through a nozzle; simulation shows that water can be cooled to near freezing temperatures depending on the water-to-air mass flow ratio; indicates that the coefficient of performance (COP) is only approximately 0.25, but that it might be improved [speculative] to 2.0 in a closed cycle with kinetic energy recovery from the expansion process; not-in-kind (NIK) technology; includes discussion by A. Ophir (Ide Technologies Limited, Israel)

B. L. Minner, J. E. Braun, and L. G. Mongeau (Purdue University), **Theoretical Evaluation of the Optimal Performance of a Thermoacoustic Refrigerator,** paper PH-97-12-2, *Transactions* (Winter Meeting, Philadelphia, PA, 26-29 January 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 103(1):873-887, 1997 (15 pages with 10 figures and 8 tables, RDB7C24)

not-in-kind (NIK) technology, thermoacoustic refrigeration using R-704 (helium), R-7131 (xenon), and R-704/7131 (50/50) as the refrigerant

F. Steimle and K. Schiefelbein (Universität Essen), **Stirling Refrigeration Systems as an Alternative to Perkins-Evans Cycles**, *Heat Pump Systems, Energy Efficiency and Global Warming* (proceedings of the IIR conference, Linz, Austria, 28 September - 1 October 1997), publication 1997/4, International Institute of Refrigeration (IIR), Paris, France, 173-181, 1997 (9 pages with 8 figures, RDB9333)

summarizes simulations of a Stirling cycle using R-704 (helium) as the refrigerant and limited validation of the predicted results

M. J. E. Verschoor and P. A. Oostendorp (Netherlands Organization for Applied Scientific Research, TNO, The Netherlands), **Air Cycle Heat Pump Developments and Applications,** *Heat Pumps - a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 9, 1999 (7 pages with 2 figures, RDB9842)

R-729 (air), Joule-Brayton cycle

Proceedings of the 1993 Non-Fluorocarbon Insulation, Refrigeration, and Air-Conditioning Technology Workshop (Wiesbaden, Germany, 27-29 September 1993), report ORNL-6805, Oak Ridge National Laboratory, Oak Ridge, TN, 1994 (344 pages, available from JMC as RDB5270)

These proceedings provide background papers and summary comments on alternative technologies for air-conditioning, refrigeration, and insulation. The papers address blowing agents for insulating foams, including R-245ca, R-245eb, R-245fa, R-356, R-601 (pentane), R-718 (water), and cyclopentane, as well as a screening of hydrofluoropropane isomers. They also address nonorganic fibers, gas-filled and vacuum panels, aerogels and aerogel panels, and other materials and not-in kind (NIK) technologies. A paper on air conditioning and refrigeration cycles details comparative primary energy requirements for compression and absorption systems, with selected power supply systems. Others address gas-fired systems, water-zeolite absorption, Stirling cycles, thermoacoustic refrigeration, use of water as refrigerant and heat transfer fluid, direct and indirect use of outdoor air and groundwater, storage for desiccant cooling systems, and air cycles. Papers on alternative refrigerants address R-C270 (cyclopropane), R-290 (propane), R-600 (n-butane), R-600a (isobutane), R-290/600a blends, R-717 (ammonia), R-729 (air), and R-744 (carbon dioxide).

Refrigeration and Air-Conditioning Technology Workshop, proceedings of the 1993 Non-Fluorocarbon Refrigeration and Air-Conditioning Technology Workshop (Breckenridge, CO, 23-25 June 1993), edited by P. J. Lewis and D. M. Counce, report ORNL-6797, Oak Ridge National Laboratory, Oak Ridge, TN, 1994 (308 pages with summary and 18 papers, available from JMC as RDB4891)

These proceedings provide an assessment and background papers on alternatives to, and anticipated advances in, air-conditioning and refrigeration systems using fluorocarbon refrigerants. They address a number of vapor compression areas, including use of hydrocarbons and ammonia as refrigerants; free-piston, oil-free compressor developments; Stirling cycle refrigeration; compression-absorption hybrid cycles; sonic and thermoacoustic compression; hydraulic and Malone cycle hydraulic refrigeration; and advanced fluorocarbon systems. They also address absorption, adsorption, sorption, metal hydride, evaporative, desiccant, magnetic refrigeration, and thermoelectric cooling technologies. The introduction outlines the process followed and invitation of expert speakers, to outline the not-in-kind (NIK) and advanced technologies. It also identifies a panel assembled to conduct the sessions and compile technology summaries. These summaries are included along with the workshop agenda, list of participants, presented papers or presentation charts, questions addressed to speakers, and for those received responses. This workshop was one of two, the second held in Germany, on the subject.

RESEARCH PROGRAMS

M. O. McLinden (National Institute of Standards and Technology, NIST, USA) and L. Vamling (Chalmers University of Technology, Sweden), **The Need for, and Availability of, Fluid Property Data: Results from Annexes XIII and XVIII,** proceedings of the 4th International Energy Agency (IEA) Heat Pump Conference (Maastrict, The Netherlands, 26-29 April 1993), IEA Heat Pump Centre, Sittard, The Netherlands, April 1993 (12 pages, available from JMC as RDB3703)

J. A. Manzione (U.S. Army), **Development of Carbon Dioxide Environmental Control Unit for the U.S. Army,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 297-302, 1998 (5 pages with no figures or tables, RDB9225)

describes military needs and procurement approaches for unitary, mobile, air conditioners (Environmental Control Units, ECU) for comfort and equipment cooling; notes that current use of R-22 will be phased out and that the Army may pass over hydrofluorocarbons (HFCs) for R-744 (carbon dioxide) if life-cycle cost goals can be met; outlines a program to develop components and a prototype; identifies the participants as Oak Ridge National Laboratory (ORNL) for system modeling, Purdue University for component and system modeling, the National Institute of Standards and Technology (NIST) for supercritical heat transfer measurements, and the University of Maryland for compressor development; suggests that the military may be uniquely positioned to support high-risk research into R-744 applications; indicates that the early results show good potential for R-744, but much development work still is needed; includes discussion by P. Nekså (SINTEF Energy Research, Norway) and H. Halozan (Technische Universität Graz, Graz, Austria)

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A. S. Patil (U.S. Army), **Natural Working Fluids - Military Advantages and Opportunities,** *Natural Working Fluids '98* (proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 293-296, 1998 (4 pages with no figures or tables, RDB9224)

outlines the rationale for R-744 use in unitary, mobile, air conditioners (Environmental Control Units, ECU) for comfort and equipment cooling; presents a phased schedule for phaseout of chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) - mainly R-22 - refrigerants with transition to hydrofluorocarbons (HFCs), notably R-134a, R-407C, and R-410A; identifies a third transition phase in which R-744 (carbon dioxide) is being considered as a long-term solution; outlines a three-year program to develop components and a prototype; identifies the participants as Purdue University for component and system modeling, Oak Ridge National Laboratory (ORNL) for gas cooler modeling and fluid flow analysis, the National Institute of Standards and Technology (NIST) for supercritical heat transfer measurements, and the University of Maryland for compressor development; suggests that the military may be uniquely positioned to support high-risk research into R-744 applications

AFEAS

Alternative Fluorocarbons Environmental Acceptability Study, program description, AFEAS, Washington, DC, September 1995 (4 pages with 1 figure and 1 table, available from JMC RDB5C36)

This leaflet introduces the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), initiated in December 1988. The program was formed to assess the potential impacts of chlorofluorocarbon (CFC) refrigerant alternatives on the environment. AFEAS is a cooperative research effort sponsored by 11 leading chemical producers. Results were incorporated as an appendix to the *Scientific Assessment* under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. Further findings were reported in workshops and as inputs to the 1991 and 1994 assessment updates. The leaflet outlines the overall goals. The first was to identify and help resolve uncertainties regarding potential environmental effects of hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). The second objective was to stimulate prompt dissemination of scientific information to the research community, government decision makers, affected industries, and the general public. A table lists alternatives to CFCs, including HCFCs R-22, R-123, R-124, R-141b, R-142b, R-225ca, and R-225cb, as transitional substances, and HFCs R-32, R-125, R-134a, R-143a, and R-152a. The summary notes that scientific studies show that use of HCFCs and HFCs to replace CFCs will reduce the amount of atmospheric chlorine, and thus decrease the risk of ozone depletion. Unlike CFCs, these alternatives will break down readily in the lower atmosphere, forming products with negligible contribution to either acid deposition or ozone pollution. Some of the HCFCs and HFCs can be expected to form trifluoroacetyl halides that will dissolve in water to form trifluoroacetic acid. While the concentrations are so low that adverse effects are unlikely, this issue is being investigated further. A figure shows the potential future contributions from all greenhouse gases. A cited AFEAS study of global warming, co-funded with the U.S. Department of Energy, indicates that HCFCs and HFCs often provide substantial improvements in energy efficiency over CFCs in many applications. Moreover, they do not accumulate in the atmosphere to the same extent as CFCs, and have smaller potential to contribute to the greenhouse effect. The leaflet notes that AFEAS-funded research has been completed, but the organization will be continued for three years to stay abreast of scientific developments.

Research Summary, Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), Washington, DC, January 1993 (76 pages, RDB3610)

ARI

AREP Technical Committee, **R-22 Alternative Refrigerants Evaluation Program (AREP) Program Status Report**, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 16 September 1994 (10 pages with 1 table, available from JMC as RDB5250)

This report summarizes the progress and accomplishments of the Alternative Refrigerants Evaluation Program (AREP). AREP is described as a cooperative program to provide data on the performance of R-22 and R-502 equipment with alternative, non-ozone-depleting refrigerants in a quick and efficient manner. The report reviews the history of the program and cooperation by more than 30 manufacturers in Canada, Europe, and Japan in addition to those in the United States. It outlines the objectives, namely to identify alternatives, establish testing protocols, conduct tests, and publish the results. Test were conducted with 26 refrigerants, which are tabulated. They included R-134a; R-290 (propane); R-717 (ammonia); R-23/32/134a (1.5/20/78.5), (1.5/27/71.5), and (2/29.4/68.6); R-32/125 (50/50) [R-410A] and (60/40); R-32/-125/134a (10/70/20) [R-407B], (23/25/52) [R-407C], (24/16/60), (25/20/55), and (30/10/60); R-32/125/290/134a (20/55/5/20); R-32/134a (20/80), (25/75), (30/70), and (40/60); and R-125/143a (45/55) as potential replacements for R-22. They also included R-23/32/125 (5/25/70), R-32/125/134a (10/70/20) [R-407B] and (20/40/40) [R-407A], R-32/125/143a (10/45/45), R-125/143a (45/55) and (50/50) [R-507A], and R-125/143a/134a (44/52/4) [R-404A] as potential replacements for R-502, an azeotrope of R-22 and R-115. The evaluations comprised compressor calorimeter, system drop-in, soft-optimized compressor, and soft-optimized system tests. They were complimented by performance simulations by the National Institute of Standards and Technology (NIST), heat transfer tests by three universities under contract to the Electric Power Research Institute (EPRI), and heat transfer tests by one manufacturer. The resulting reports are available through the ARTI Refrigerant Database; similar future studies will be accepted and also distributed through the database. The report notes that performance was generally inferior with drop-in tests, but close to or better than with R-22 or R-502 with optimized systems. Final evaluation of the data and refrigerant selections are left to individual manufacturers. The report concludes that the program was an unqualified success and proposes continued international cooperation through both discussion forums and cooperative testing.

AREP Technical Committee, **R-22 Alternative Refrigerants Evaluation Program (AREP) Report List,** Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 13 September 1994 (6 pages with 1 table, available from JMC as RDB5251)

This document lists reports under review or available from the Alternative Refrigerants Evaluation Program (AREP) [see RDB5250]. It lists the company performing the tests, refrigerants evaluated, type of test, ARTI Refrigerant Database number, length, and approval status for each report. This list is still being revised as final reports are approved.

ARI Research Compendium, Air-Conditioning and Refrigeration Institute, Arlington, VA, October 1996 (122 pages with 2 figures and 1 table, available from JMC as RDB6C11)

This documents outlines research needs and activities to resolve issues of importance to the air-conditioning and refrigeration (ACR) industry and to assist in the identification of new ACR technologies. It summarizes the role of the Air-Conditioning and Refrigeration Institute (ARI) and outlines its research program, covering refrigerants, energy conservation, and building environment. It then summarizes the *R-22 Alternative Refrigerants Evaluation Program* (AREP) and the Air-Conditioning and Refrigeration Technology Institute (ARTI) *Materials Compatibility and Lubricant Research (MCLR) Program.* The compendium also describes other research activities, including evaluations of joining techniques for copper tubing and of flammable and toxic refrigerants. It briefly outlines assistance to national laboratories and information exchange and dissemination efforts. An appendix presents the objectives, justification, background, industry actions, and status of research addressing long-term alternative refrigerants; R-22 alternatives; R-503 alternatives; R-123 alternatives; measurement and classification of the flammability and combustibility of refrigerants and blends; global warming mitigation by refrigerant recycling; methods for recovery, reclamation, and recycling refrigerants; refrigerant monitoring and leak detection technologies; analyze the quality of refrigerants; and determine the composition of refrigerant blends. The appendix similarly presents projects in the areas of energy conservation and building environment. A second appendix summarizes the AREP tests, conclusions, and heat transfer research. A final appendix presents the objectives, research contractor, status, and related information for 25 MCLR Program projects of which eight are completed, twelve are on-going, and five are in planning. The reports resulting from the AREP and MCLR program are individually identified in and distributed through the ARTI Refrigerant Database.

ARTI

R. H. Ernst (The Trane Company), **Materials Compatibility and Lubricants Research with Alternative Refrigerants,** *R-22 and R-502 Alternatives* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 19-20 August 1993), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 91-96, 1994; republished as report DOE/CE/23810-22F, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 1993 (6 pages with 4 figures and 2 tables, available from JMC as RDB4523)

This paper summarizes research completed in Phase I of the Materials Compatibility and Lubricant Research (MCLR) Program, reviews progress on Phase II, and discusses the studies

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planned for Phase III. It emphasizes those projects examining alternatives for R-22 and R-502. It notes the focus of the initial phase as compatibility with motor materials, elastomers, and plastics; chemical and thermal stability; miscibility of lubricants and refrigerants; and thermophysical properties for ten alternative refrigerants and four types of lubricants. They include four hydrochlorofluorocarbons (HCFCs), namely R-22, R-123, R-124, and R-142b, and six hydrofluorocarbons (HFCs), namely R-32, R-125, R-134, R-134a, R-143a, and R-152a. The lubricant classes included mineral oil (MO), alkylbenzene (AB), polyolester (POE), and polyglycol (PAG). A table summarizes the results of compatibility studies of motor materials with R-22/MO and R-32, R-125, R-134a, and R-143a with a POE for magnet wires; varnishes; sheet, sleeving, and lead wire insulations; tapes, and tie cords. The paper indicates that projects for the second phase address compatibility with desiccant materials; viscosity, density, and gas solubility of refrigerant-lubricant mixtures; and development of accelerated test methods for chemical and thermal stability and for the life of motor materials. An illustrative table indicates the miscibility of a POE lubricant at 5, 25, and 60% concentrations in R-32/125 (60/40), R-32/-125/134a (30/10/60), R-32/134a (30/70), R-125/143a (45/55), and R-404A - R-125/143a/134a (44/52/4). Two figures show the modified sealed tube used for electrical conductivity and stability measurements and the measured conductivity of R-11, R-12, and R-22 with MO at 175 °C (348 °F). Two further figures illustrate a simulated motor stator test specimen and a high pressure tribometer for development of test methods. The paper identifies six projects being investigated for the third phase. They include compatibility of process fluids from manufacturing with HFCs, compatibility of additives to POEs with HFCs, development of low-cost, environmentally acceptable flushing and clean out methods, investigation of motor burnout products, fractionation of zeotropes, and development of an improved flammability test method. The paper also notes an ongoing project to facilitate location of refrigerant and lubricant information, the ARTI Refrigerant Database. The paper identifies the members of the MCLR Advisory committee and acknowledges major sponsorship of the MCLR Program by the U.S. Department of Energy.

G. C. Hourahan (Air-Conditioning and Refrigeration Technology Institute, ARTI), **21-CR: A Recently-Launched U.S. Research Effort,** *Heat Pumps – a Benefit for the Environment* (proceedings of the Sixth International Energy Agency (IEA) Heat Pump Conference, Berlin, Germany, 31 May - 2 June 1999), Verlags- und Wirtschaftsgesellschaft der Elektrizitätswerke m.b.H. (VWEW-Verlag), Frankfurt am Main, Germany, posters tab 12, 1999 (9 pages with 1 figure, RDB9844)

introduces the "HVAC&R Research for the 21st Century" (21-CR) program and its focus, organization, and potential participants; notes that the program will undertake precompetitive research to resolve technological hurdles and difficulties that prevent or impede manufacturers from commercializing "next-generation" components and systems; identifies five strategic areas of research including alternative equipment, high-efficiency equipment, system integration, indoor environmental quality, and environmentally-friendly working fluids; notes the need for research addressing safety (toxicity, flammability, decomposition, and application), materials compatibility, reliability, and performance issues for new refrigerants

M. S. Menzer (Air-Conditioning and Refrigeration Institute, ARI), W. E. Noel (U.S. Department of Energy, DOE), S. R. Szymurski (ARI), **Lessons Learned from the ARTI Materials Compatibility and Lubricants Research Program,** *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVa:412-419, 1995 (8 pages with 2 tables, rdb7841)

This paper summarizes a joint industry-government program, the ARTI Materials Compatibility and Lubricants Research (MCLR) Program, to address the issues associated with adopting potential new refrigerants in air-conditioning and refrigeration equipment. It highlights the key results for materials compatibility with focus on stability, miscibility, motor materials, elastomers, plastics, desiccants, and other areas. It also summarizes sponsored research of thermophysical properties, electrohydrodynamic (EHD) enhancement of heat transfer, improved test methods, and the operations and safety aspects (flammability, fractionation, and toxicity) of alternative refrigerants. It similarly addresses the products of compressor-motor burnouts, lubricant circulation, lubricant foaming, flushing and clean-out methods, system contaminant levels, evaluation of R-245ca as a low-pressure refrigerant, and information dissemination. The paper acknowledges major sponsorship of the MCLR Program by the U.S. Department of Energy.

ARTI MCLR Program, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, continuous since January 1996 (available from the Internet at http://www.ari.org/rt/mc_sum.html, RDB6905)

Summaries of technical progress are posted for current and completed projects, as well as those open for bids, in the Materials Compatibility and Lubricant Research (MCLR) Program. The program supports critical research to accelerate introduction of substitutes for chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants. It addresses refrigerant and lubricant properties, materials compatibility, and test methods development. This work is jointly funded under a grant from the U.S. Department of Energy and cost sharing by the air-conditioning and refrigeration industry. Summaries identify the title, objective, contractor, principal investigator, and project status for each project. They also indicate report availability and briefly summarize the work, materials tested, and findings. [These reports are available through the ARTI Refrigerant Database along with other MCLR reports and conference papers.]

ASHRAE

1997-1998 ASHRAE Research Plan, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1 January 1997 (24 pages with 7 tables, RDB7269)

This list of prospective research subjects identifies 290 proposed projects, 51 designated as *priority* status. The projects are grouped into eight project classifications, based on approved funding guidelines. Projects relating to refrigerants fall in several of these categories, primarily including the fourth and sixth highest areas, *Environmentally-Safe Materials and Refrigeration Systems*. The research areas were proposed by ASHRAE Technical Committees, Task Groups, and other committees; they were prioritized by ASHRAE's Research and Technical Committee. The highest priority group (*three stars*) includes research of *Thermophysical Properties of R-23, Chloride, Fluoride, and Acidity Measurements of CFC, HCFC, and HFC Refrigerants*, and *Evaporation of Ammonia Outside Smooth and Enhanced Tubes with Miscible and Immiscible Oils*. The next classification includes *Investigation of Major Sources of Refrigerant Emissions and Feasible Methods for Reducing These Emissions* and *The Effects of Inundation and Miscible Oil upon Enhanced Condensation Heat Transfer of Alternative Refrigerants for HVAC Applications*. It also includes *HFC Refrigerant-Lubricant Modeling for Gas Solubility and Lubricant Viscosity,* identified as a *high-risk* project. The one-star priority group includes *Transport Property Data for Refrigerant Blends* and *Measurement of Solubility, Viscosity, and Density of R-32/ 125 (R-410 Series) Refrigerant-Lubricant Mixtures*. Among nonpriority projects are: *Assessment of Vibration Insulation Material Compatibility with R-22, Alternative Refrigerants, and Ethylene Glycol Mixtures, Boiling and Condensation in a High-Vibration Environment, Thermophysical Properties of R-245ca, Comprehensive Thermodynamic Property Data for Refrigerant Blends, Measurement of R-22 and Alternative Refrigerant Leakage Rates from Open-Shaft Compressors, Double-Walled Heat Exchangers for Class 2 Refrigerants, Heat and Mass Transfer Additives in Aqua Ammonia Systems, Experimental Evaluation of the Heat Transfer Impacts of the Use of an Immiscible and Insoluble Lubricant-Refrigerant Pair, Boiling and Two-Phase Flow of Ammonia and Ammonia-Oil Mixtures in a Corrugated Passage Simulating a Plate Heat Exchanger, Performance Comparison of Different Refrigerants in Flat-Plate, Microchannel Evaporators, Nonequilibrium Effects of Evaporation and Condensation of Zeotropic Refrigerant Mixtures, Identification of Tradeoffs Among Secondary Coolants in Various Very Low Temperature Applications, Develop Solubility and Viscosity Data for Various Oil-Refrigerant Mixtures at High Discharge Temperatures and Pressures*, *"Performance of a Suction-Line Capillary-Tube Heat Exchanger, Performance of an Adiabatic Capillary Tube with Zeotropic Mixtures, Effect of Motion of an Ammonia Air Mixture in an Enclosed Space on Explosivity, Separating Velocities for Ammonia in Horizontal and Vertical Vessels, Refrigerant Piping Pressure Drop Computer Program, Evaluation of Soldered and Brazed Joints in Copper Tubing, Optimizing Refrigeration for High* T_c *Superconducting Applications and Systems*. This plan summarizes anticipated funding and procedures for implementing the research identified; it replaces versions published for preceding years [see RDB6301]. [EDITORIAL NOTE: A liberal view was used to identify projects relating to refrigerants from this Research Plan. Comparison to counterparts from the prior two years suggests that very few identified topics, whether or not designated as priority projects, progress to work statements and actual accomplishment. Moreover, some of the identified projects are, at best, ideas for the future whose time has past.]

IEA

J. Stene (SINTEF Energy Research, Norway), **Compression Systems with Natural Working Fluids - Results and Conclusions from IEA Annex 22 (1995-98)**, *Natural Working Fluids '98*

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(proceedings of the IIR - Gustav Lorentzen Conference - meeting of Commissions B1, B2, E1, and E2, Oslo, Norway, 2-5 June 1998), publication 1998/4, International Institute of Refrigeration (IIR), Paris, France, 171-179, 1998 (9 pages with 2 tables, RDB-9212)

describes an international program of cooperative data collection and sharing on the use of R-290 (propane), R-290/600a (propane/isobutane) blends, R-717 (ammonia), R-718 (water), R-729 (air), R-744 (carbon dioxide), a system employing carbon dioxide and ammonia in a cascade, and carbon dioxide as a heat transfer fluid in a secondary-loop system with ammonia as the refrigerant in heat pump systems; describes participation and preparation of national reports by teams from eight participating countries, workshops, and dissemination efforts including reports and postings on an Internet web site; indicates that workshops were conducted in Trondheim Norway in October 1995, Gatlinburg TN USA in October 1997, and Tokyo Japan in February 1998; the effort outlined is identified as Annex 22 to the Heat Pump Programme of the International Energy Agency (IEA); includes discussion by J Bouma (IEA Heat Pump Center, The Netherlands), R. Krauss (Universität Stuttgart, Germany), and P-E. Frivik (SINTEF Energy Research, Norway)

PAFT

Programme for Alternative Fluorocarbon Toxicity Testing, program description, PAFT, Washington, DC, September 1995 (4 pages with 1 table, available from JMC as RDB5C38)

This leaflet outlines the Programme for Alternative Fluorocarbon Toxicity Testing (PAFT), which was initiated in December 1987. The program was designed to expedite the development of toxicology data for possible substitute fluorocarbons, to replace chlorine-containing compounds such as chlorofluorocarbons (CFCs). PAFT is a cooperative research effort sponsored by 16 of the leading CFC producers from eight countries. Five PAFT program sectors are identified including PAFT I to address R-123 and R-134a, PAFT II for R-141b, PAFT III for R-124 and R-125, PAFT IV for R-225ca and R-225cb, and PAFT V for R-32. The leaflet summarizes objectives, schedules, and results of each of these programs. It notes that the eight cited compounds have been exhaustively tested though more than 200 individual toxicology studies performed in testing laboratories in Europe, Japan, and North America. All of these investigations have been completed except general studies of mechanistic, metabolic, and pharmacokinetic aspects of the toxicology of fluorocarbons, which are not compound specific. The program has cost 21 million dollars in addition to in-house studies, by the sponsoring companies, suggested as costing a similar amount. The results have been reported to regulatory bodies, presented at scientific conferences, used in international assessments, and will be published in peer-reviewed journals. The program assessed acute, subchronic, developmental, and chronic toxicity, carcinogenicity, genotoxicity, and environmental toxicology studies.

Testing to Extremes - Industry's Cooperative Effort to Test the Health and Safety of Selected Fluorocarbon Alternatives to CFCs, Programme for Alternative Fluorocarbon Toxicity Testing (PAFT), Washington, DC, circa 1996 (12 pages with 1 figure and 2 tables, RDB65E9)

This leaflet describes the Programme for Alternative Fluorocarbon Toxicity Testing (PAFT), outlines its history, and reviews the hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) compounds addressed. Cited goals were to determine potential health and environmental effects of chlorofluorocarbon (CFC) alternatives in accordance with international guidelines; to derive toxicity information through a rapid, cost-effective program that pooled the resources of member companies and shared the results; and to ensure rapid publication of the results. Five program sectors are identified including PAFT I to address R-123 and R-134a, PAFT II for R-141b, PAFT III for R-124 and R-125, PAFT IV for R-225ca and R-225cb, and PAFT V for R-32. The leaflet summarizes a basic test schedule consisting of studies of acute toxicity, cardiac sensitization, genotoxicity, subchronic toxicity, developmental toxicity, and chronic toxicity and carcinogenicity. It notes that further tests were added according to the physical properties, intended application, or expected exposure regime of the chemical. Among them were dermal toxicology, reproductive toxicology, neurotoxicity, ecotoxicology, and metabolism studies. These studies have been completed except for a general study of the mechanistic, metabolic, and pharmacokinetic aspects of fluorocarbon toxicology. The leaflet documents inputs from PAFT to the international and national processes addressing CFC phaseout and to the scientific community. It identifies the member companies and testing laboratories that participated, the latter from Europe, North America, and Japan. It also provides brief summaries of findings for R-32, R-123, R-124, R-125, R-134a, R-141b, R-225ca, and R-225cb. The document concludes with a description of the operation of PAFT and list of presentations and publications.

NEDO

T. Ohira and K. Yamagishi (New Energy and Industrial Technology Development Organization, NEDO, Japan), **Introducing the R&D Programs Concerning CFC-Related Technologies Implemented by MITI/NEDO**, *Stratospheric Ozone Protection for the 90's* (proceedings of the International CFC and Halon Alternatives Conference, Washington, DC, 23-25 October 1995), Alliance for Responsible Atmospheric Policy, Arlington, VA, 294-302, October 1995 (9 pages, available from JMC as RDB5B04)

refrigerant development, reclaim, and destruction

MISCELLANEOUS DOCUMENTS

J. J. Beall (Calpine Corporation), M. C. Adams (University of Utah Energy and Geosciences Institute), and P. N. Hirtz (Thermochem, Incorporated), **Evaluation of R134a as an Injection Water Tracer in the Southeast Geysers**, *Transactions*, Geothermal Resources Council, 22:569-573, 20-23 September 1998 (5 pages with 6 figures and 1 table, RDB-8B31)

test of R-134a to replace R-13 in mapping flow paths in hydrogeological studies; laboratory tests of the chemical stability of R-134a at 280 °C (536 °F)

J. M. Calm (Engineering Consultant), **Refrigerant Database**, report 21CR/00010-01, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, 15 September 1999 (468 pages with 1 table, available from JMC as RDB9930)

This document provides bibliographic citations for 3248 publications that may be useful in research, design, and application of air-conditioning and refrigeration equipment. Synopses of the content, materials addressed, and key conclusions are provided for approximately 40% of these documents. The database identifies sources of specific information on R-22, R-23, R-32, R-41, R-116, R-123, R-124, R-125, R-134, R-134a, R-141b, R-142b, R-143a, R-152a, R-218, R-227ea, R-236fa, R-245ca, R-245fa, R-290 (propane), R-C318, R-600 (butane), R-600a (isobutane), R-717 (ammonia), R-718 (water), R-744 (carbon dioxide), R-1270 (propylene), ethers, and others as well as azeotropic and zeotropic blends of these fluids. These blends include R-400, R-401A, R-401B, R-401C, R-402A, R-402B, R-403A, R-403B, R-404A, R-405A, R-406A, R-407A, R-407B, R-407C, R-407D, R-408A, R-409A, R-409B, R-410A, R-410B, R-411A, R-411B, R-412A, R-413A, R-414A, R-414B, R-415A, R-416A, R-500, R-501, R-502, R-503, R-504, R-505, R-506, R-507A, R-508A, R-508B, R-509A, and others for which information is available, even though standard designations may not have been assigned yet. It also addresses mineral oil, alkylbenzene, polyalkylene glycol (PAG), polyolester (POE), and other lubricants. It references documents on compatibility of refrigerants and lubricants with desiccants, elastomers, metals, plastics, motor insulation, and other materials used in refrigerant circuits. The database is available in both a computerized version and as a listing in report form. The computerized version includes more than 6000 citations, including those in the report version, others from a supplement on copper in air conditioning and refrigeration, and an archival group covering historical and superseded documents. The computerized version also includes 606 specially prepared data summaries, including refrigerant (single compound and blend) profiles, tabular compatibility summaries for plastics and elastomers, and toxicity reviews for refrigerants. More than 8,000 pages of reference material can be searched and selectively printed using accompanying retrieval software, which enables very fast searches for user-selected terms or combinations of terms. The search program offers several automated features to simplify searches including optional prompting by search category, an automated "thesaurus" of synonyms and related terms, chain searches to broaden or narrow prior searches, a "wildcard" capability to allow entry of word segments, and a configuration capability to customize a number of options. Both the report and computerized versions include instructions to obtain cited documents or subscriptions for database updates.

J. M. Calm (Engineering Consultant), **Copper in Air Conditioning and Refrigeration - Supplement to the ARTI Refrigerant Database,** report JMC/-ARTI/CDA-9901D, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, and the Copper Development Association (CDA), New York, NY, January 1999 (104 pages with no figures or tables, available from JMC as RDB9133)

This document provides bibliographic citations for more than 600 publications that may be useful in research, design, and application of air-conditioning and refrigeration (ACR)

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equipment. Summaries or brief descriptors of the content, materials addressed, and key conclusions are provided for the majority. This supplement to the ARTI Refrigerant Database increases the information provided, by focusing on the suitability of and application data for copper and copper alloys with refrigerants. The key concentration areas are application data, compatibility, and heat transfer (including surface enhancement). An introduction outlines the reasons copper is the preferred fabrication material in many ACR components. It cites the metal's superior heat transfer properties, corrosion resistance, ease of fabrication and joining, strength, and machinability. It also notes the latitude afforded by copper, brass, bronze, and other alloys in manufacturing processes such as casting, forging, machining, drawing, sintering, and forming. A concluding section provides descriptions of both the Refrigerant Database and the Copper Data Center (CDC) database.

D. Clodic (École des Mines de Paris, France), **Major Technical Options Aiming to the Limitation of Ozone Depleting Substances (ODS) Consumption in Commercial Refrigeration**, *The Earth Technologies Forum* (proceedings, Washington, DC, 26-28 October 1998), Alliance for Responsible Atmospheric Policy, Arlington, VA, 247-253, October 1998 (6 pages with 4 figures, RDB8B21)

summary of the findings for commercial refrigeration from an international assessment for the United Nations Environment Programme (UNEP) Technical Options Committee (TOC) report on refrigeration, air conditioning, and heat pumps: outlines the uses of refrigerants in central systems, condensing units for split systems, and stand-alone equipment; discusses uses of R-717 (ammonia), R-744 (carbon dioxide), and hydrocarbons as replacements for fluorochemical refrigerants; describes progress in application of indirect systems and containment (leak reduction)

P. A. Domanski (National Institute of Standards and Technology, NIST), **Refrigerants for the 21st Century - ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, October 6-7, 1997**, conference report, *Journal of Research of the NIST*, National Institute of Standards and Technology (NIST), Gaithersburg, MD, 103(5):529-533, September-October 1998 (5 pages with 1 table, available from JMC as RDB9128)

summarizes the highlights and conclusions of 16 invited papers that provide updates and projections on refrigerant trends and research; covers environmental concerns including stratospheric ozone depletion and global warming, trade-offs in refrigerant selections, hydrofluorocarbon (HFC) and other organic fluids including hydrofluoroethers, alternatives to HFC technologies, hydrocarbons, R-717 (ammonia), R-744 (carbon dioxide), and secondary heat transfer loop systems; concludes that a consensus option was neither expected nor developed, that HFCs will be dominant for decades if not perturbed by new regulatory measures, and that the search for new and refinement of existing technologies will continue

H. M. Hughes (AlliedSignal Incorporated), **Contemporary Fluorocarbons,** *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 117-121, 1997 (5 pages with 1 figure and 4 tables, RDB7B14)

reviews the transition from chlorofluorocarbon (CFC) to hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) refrigerants: reviews current refrigerants and CFC and HCFC alternatives noting R-123 as the primary alternative for R-11, R-134a for R-12 and R-500, R-23 for R-13, R-410A for R-13B1, no replacement for R-113, R-236fa (planned) for R-114, R-404A and R-507A for R-502, and R-508B for R-503; presents a tabular comparison of the influences of subcooling on the choice among R-11, R-123, and R-245fa; indicates that R-245fa has emerged as the most likely candidate to replace R-123 by a process of elimination, and that transport property advantages for R-245fa may overcome its thermodynamic shortcomings; also indicates that R-410A "has been selected for the majority of applications" to replace R-22, but notes a role for R-407C at least for the short-term

T. B. Coplen and H. S. Peiser (U.S. Geological Survey, USGS) for the International Union of Pure and Applied Chemistry (IUPAC) Commission on Atomic Weights and Isotopic Abundances, **History of the Recommended Atomic Weight Values from 1882 to 1997: A Comparison of Differences from Current Values to the Estimated Uncertainties of Earlier Values**, *Pure and Applied Chemistry*, 70(1):237-257, 1998 (21 pages, available from JMC as RDB8820)

definitive atomic weights used to calculate the molecular mass of refrigerants

F. J. Keller (Carrier Corporation), **An Overview of the UNEP Technical Options Committee Report on Air Conditioners and Heat Pumps**, *The Earth Technologies Forum* (proceedings, Washington, DC, 26-28 October 1998), Alliance for Responsible Atmospheric Policy, Arlington, VA, 254-263, October 1998 (10 pages with 3 figures and 8 tables, RDB8B22) summary of the findings for air conditioners and heat pumps from an international assessment for the United Nations Environment Programme (UNEP) Technical Options Committee (TOC) report on refrigeration, air conditioning, and heat pumps: provides an estimate of the current inventory of units and the quantity of R-22 used in them (239 million units containing approximately 423 kt, 930 million lb), outlines the options to replace R-22 with specific mention of R-290 (propane), R-407C, R-410A, and R-744 (carbon dioxide); discusses retrofit options with focus on R-407C; predicts demand for R-22 in developed and developing countries through 2015 and estimates the portion that can be met with recycled R-22; summarizes a model to estimate refrigerant needs based on leakage data, production projections, and assumptions for product life

H. H. Kruse and T. Tiedemann (Universität Hannover, Germany), **Experience with HC Refrigerants and Projections for Future Applications,** *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 44-56, 1997 (13 pages with 8 figures and 2 tables, RDB-7B06)

review of the recent history and status of use of hydrocarbons as refrigerants in domestic refrigeration, air-conditioning and heat pump systems, and commercial refrigeration; also addresses standards for refrigerant safety applicable to hydrocarbon use, related research, and projections for hydrocarbon use

K. S. Sanvordenker (Consultant), **Status of CFC and HCFC Alternatives**, *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 111-116, 1997 (6 pages with no figures or tables, RDB7B13)

status chlorofluorocarbon (CFC), CFC alternative, hydrochlorofluorocarbon (HCFC), HCFC alternative, hydrofluorocarbon (HFC), and HFC alternative refrigerants: concludes that there is an adequate supply of CFCs for near-term service needs and that conversion from CFCs to HFCs is successful; notes that conversion from HCFCs to HFCs is "on its way although not at commercial levels"; presents both a historical perspective and a rationale why HFCs should become permanent replacements for CFCs and HCFCs

M. Sakamoto (Tokyo Metropolitan University, Japan), **New Refrigerants for Japan's Heat Pump and Refrigeration Markets,** *IEA Heat Pump Center Newsletter - CFC and HFC Replacement*, International Energy Agency (IEA) Heat Pump Center (HPC), Sittard, The Netherlands, 13(1):22-24, March 1995 (3 pages with 3 figures, RDB5687)

status of alternative refrigerant use in Japan

F. Sauer (Dehon Service, France), **Containment and Leakage**, *The Earth Technologies Forum* (proceedings, Washington, DC, 26-28 October 1998), Alliance for Responsible Atmospheric Policy, Arlington, VA, 264-269, October 1998 (6 pages with 2 tables, RDB8B23)

summary of the findings for refrigerant management from an international assessment for the United Nations Environment Programme (UNEP) Technical Options Committee (TOC) report on refrigeration, air conditioning, and heat pumps: outlines the past and current coverage of refrigerant recovery, recycling, and reclamation in the assessment; tabulates annual rates of refrigerant recovery, reclamation, and sales from 1987-1995 in France; similarly summarizes losses from R-11 and R-12 chillers; discusses the need for measures to increase refrigerant conservation to reduce emissions

P. Weiss and J. Goguet (Elf Atochem S.A., France), **Current and Projected Use of Refrigerants in Europe**, *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 38-43, 1997 (6 pages with 4 figures, RDB7B05)

review of the European market for refrigerants: current and projected uses in domestic, commercial, industrial, and transport refrigeration; trends in mobile and stationery air conditioning; concludes that while the market is dominated by fluorochemicals, their use is projected to shrink significantly; use of hydrocarbons (largely R-600a, isobutane) and R-717 (ammonia) is expected to increase from 10-12% to approximately 15%, largely based on increased use of R-717 in industrial refrigeration; notes that more than 90% of refrigerators sold in Germany use R-600a with high use in Austria and Switzerland as well

Chilling Facts About a Burning Issue - CFC Smuggling in the European Union, Environmental Investigations Agency, 15 Bowling Green Lane, London, EC1R 0BD, UK, 1998 (available from publisher for $10.00; rdb8510)

describes black market scams, identifies those involved, and outlines a sting operation

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Manual for Reductions in the Use of Ozone Depleting Substances (second edition), Japan Industrial Conference for Ozone Layer Protection, Tokyo, Japan, February 1992 (140 pages, available from JMC as RDB2705)

This manual outlines technologies for reduction and substitution of chlorofluorocarbons (CFCs) and other ozone-depleting substances (ODSs). It is intended to assist ODS users to develop the most effective measures for each application. Section III.4 addresses leak prevention and use reduction for refrigerants as well as research and development of substitute refrigerants and technologies to use them. It briefly summarizes reduction measures for centrifugal chillers, automobile air conditioners, commercial refrigeration, transport refrigeration, and refrigerators. Other sections of this document review regulatory measures for refrigerants, toxicity and safety evaluation of alternatives, and the physical properties of ODSs and their alternatives.

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