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AHRI Project 8006 – Low Global Warming Potential (GWP) Refrigerants, Phase II

Defining the Configurations of Residential Air-Conditioning and Heat Pump Systems Using Hydrocarbons, Ammonia, Carbon Dioxide, and HFO-1234yf as Refrigerants and Meeting Previously Defined Safety Requirements

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Executive Summary

As concerns about the global warming potential (GWP) of common fluorocarbon refrigerants have mounted in recent years, lower GWP refrigerants have garnered increasing attention. Among the options being evaluated are hydrocarbons like propane, ammonia, carbon dioxide (CO_2), and newly developed refrigerants like hydrofluoroolefins (HFOs). Industry is seeking alternative refrigerants which have low flammability as well as low GWP, combined with good thermodynamic efficiency and thermodynamic properties similar to those of conventional refrigerants.

In order to assess the viability of using candidate low-GWP refrigerants in ducted residential air conditioners and heat pumps, system configurations consistent with safety requirements and performance goals must be defined. Applicable codes and standards contain the relevant safety requirements. The costs and other relevant features of these system configurations (i.e. technical risk, suitability for the large replacement market, etc.) must be determined. This evaluation provides a first step towards completing such assessments by (a) identifying current applicable codes and standards that would dictate system design requirements, (b) development of the most attractive system configurations compliant with the applicable codes for four candidate low-GWP refrigerants, and (c) definition of system configuration design details.

The four candidate refrigerants considered in this work include propane, ammonia, carbon dioxide, and HFO-1234yf. All of these have low GWP, but some have potential drawbacks such as flammability, toxicity, potentially low efficiency, and/or operating conditions that are very different from those of conventional refrigerants.

Our study included three tasks:

1. Perform a review of current U.S. standards that guide the design of residential air-conditioning equipment.
2. Evaluate and compare different system design configurations for the alternative refrigerants under consideration. The configurations should be compatible (if possible) with conventional split-system designs and provide both air-conditioning and heat pumping.
3. Provide detailed descriptions of the best candidate system configuration for each of the alternative refrigerants under consideration, which will serve as a starting point for future design investigations.

Table 1-1 below shows the equipment configurations selected for each candidate refrigerant and a justification for the selection.

Table 1-1: Selected Configurations for All Refrigerants

Refrigerant	Configuration	Justification
Carbon Dioxide	Direct split-system	No restriction on use of direct split-systems, which offer the best choice of efficiency, cost, and compatibility with current systems.
Ammonia	Indirect	RCL limits for ammonia in ASHRAE 34 make direct configurations impractical.
Propane	Direct room air conditioner	Safety standards limit the potential configurations to direct room air conditioner configurations.
HFO-1234yf	Direct split-system	Some restriction on use of direct split-systems, based on charge limits, but preliminary analysis shows that this issue can be addressed using design approaches that minimize charge. Direct split-systems offer the best choice of efficiency, cost, and compatibility with current systems.

This report presents the following key findings, summarized for each refrigerant type.

<u>Carbon Dioxide</u>

According to the safety requirements provided in ASHRAE Standard 15 and UL 1995, carbon dioxide systems are not limited in charge size or in their design. However, carbon dioxide systems must meet general strength requirements for all refrigerant-containing parts, requirements that are more restrictive for carbon dioxide due to the relatively high pressures of a transcritical carbon dioxide system.

Table 1-2 below contains a summary of all relevant requirements.

Table 1-2: Summary of Requirements for Carbon Dioxide

Requirements	Source of Requirement
Strength requirements for pressure	UL 1995

Based on our requirements, our selected configuration for carbon dioxide is a 3-ton split-system heat pump. Such a system has not been commercialized, nor is there published information available that documents the viability of the specific suggested design. Key questions regarding technical readiness of the system are associated with robust operation of the refrigerant expander, the expander and overall system efficiency level, and the use of microchannel heat exchangers as the outdoor coils for heat pumps.

Table 1-3 below contains a list of the key components in the carbon dioxide configuration.

Table 1-3: Key Components for Carbon Dioxide Configuration

Components	Refrigerant System Specific Features
Heat Exchangers	Microchannel Indoor Coil, Microchannel Outdoor Coil
Compressor	Hermetic 3-ton rotary compressor
Expansion Device	Hermetic scroll expander/generator for work-recovery with power electronics and controls for conversion to 60Hz power while maintaining optimized high-side pressure.[1]
Additional Refrigerant Cycle Features	Reversing valves to reverse refrigerant flow for heat pumping, Refrigerant Charge Compensator, Suction Line Accumulator

[1]: Expander efficiency in the range of 60-70% would likely be required to approach parity with conventional HFC systems.

Ammonia

According to the safety requirements provided in ASHRAE Standards 15 and 34, and UL 1995, use of ammonia is very restricted in direct systems and not restricted in indirect systems. The driving design requirement is the ASHRAE Standard 34 RCL limits that only allow very small quantities of ammonia refrigerant in direct systems (compared to typical systems). There are no charge restrictions for indirect systems.

Table 1-4 below contains a summary of all relevant requirements.

Table 1-4: Summary of Requirements for Ammonia

Requirements	Source of Requirement
6.6 lbs charge restriction in (direct) unit systems	ASHRAE 15
Heavily restrictive RCL limit of 0.014 lbs/mcf in high probability systems	ASHRAE 34 and 15
No copper or copper-containing alloys in contact with ammonia refrigerant	ASHRAE 15, UL 1995

Based on our requirements, the selected configuration for ammonia is a 3-ton heat-pump chiller system. The heat-pump chiller configuration is best suited to meet the RCL requirements for ammonia in ASHRAE Standards 15 and 34, which are much lower than those for other candidate refrigerants. Such a system has not been commercialized, nor are there known prototypes with the specific characteristics listed below. The key question regarding technical readiness of the system is associated with the use of microchannel heat exchangers as the outdoor coils for heat pumps.

Table 1-5 below contains a list of the key components in the ammonia configuration.

Table 1-5: Key Components for Ammonia Configuration

Components	Refrigerant System Specific Features
Heat Exchangers	Brazed-Plate Evaporator, Microchannel Condenser, Hydronic Air Handler
Compressor	Hermetic ammonia scroll compressor
Expansion Device	2 Bi-Directional Expansion/Check Valves
Connective Tubing	Steel Tubing
Efficiency Enhancement Features	None[1]
Additional Refrigerant Cycle Features	Reversing valve to reverse refrigerant flow for heat pumping, Refrigerant Charge Compensator, Suction Line Accumulator
Secondary Loop Features	Water-Propylene Glycol loop serving Hydronic Air-Handler, Propylene Glycol Pump, Expansion Tank with Diaphragm

[1]: No energy-efficiency enhancements beyond the inherent efficiency advantages of using ammonia

Propane

According to the safety requirements provided by ASHRAE 15, UL 1995 and UL 484, use of propane is highly restricted. ASHRAE Standard 15 does not allow the use of A3 refrigerants in configurations other than portable-unit systems containing up to 150g of refrigerant, and UL Standard 484 allows certain charge sizes based on the LFL of the refrigerant; for example, up to 150g of propane in room air conditioners without restriction (consistent with ASHRAE Standard 15 requirements) and up to 1 kg of propane with charge restrictions based on room size. The ASHRAE Standard 15 restriction effectively precludes consideration of the larger charge allowances of UL Standard 484.

Table 1-6 below contains a summary of all relevant requirements.

Table 1-6: Summary of Requirements for Propane

Requirements	Source of Requirement
Restriction of design to room air conditioner systems with no more than 150g charge	ASHRAE 15
Electrical Equipment Requirements	UL 484
Ability to resist drop test	UL 484

Based on our requirements, the selected configuration for propane is a 0.34 ton cooling and heating room air conditioner system. The room air conditioner has been designed to use 150 g of propane as a refrigerant. The room air conditioner configuration is the only configuration that meets the requirements of ASHRAE 15 and UL 484. Such a system has not been commercialized, nor are there known prototypes with the specific characteristics listed below. The key question regarding technical readiness of the system is associated with the use of microchannel heat exchangers as the outdoor coils for heat pumps.

Table 1-7 below contains a list of the key components in the propane configuration.

Table 1-7: Key Components for Propane Configuration

Components	Refrigerant System Specific Features
Heat Exchangers	Microchannel Evaporator, Microchannel Condenser
Compressor	R-290 Rotary Compressor
Expansion Device	2 Capillary Tubes
Unique Safety Features	• All electrical components should be ignition-proof, separated from the main chamber, or be located in an enclosure • Totally-enclosed air-over double-shafted motor
Additional Refrigerant Cycle Features	Reversing valve to reverse refrigerant flow for heat pumping

HFO-1234yf

According to the safety requirements provided in ASHRAE Standard 15 and UL 1995, use of HFO-1234yf is somewhat restricted in direct systems and not restricted in indirect systems. ASHRAE Standard 15 restricts A2 systems using direct configurations to unit systems using no more than 6.6 lbs of charge. There are no charge restrictions for indirect systems.

Table 1-8 below contains a summary of all relevant requirements.

Table 1-8: Summary of Requirements for HFO-1234yf

Requirements	Source of Requirement
6.6 lbs charge restriction in (direct) unit systems	ASHRAE 15

Based on our requirements, the selected configuration for HFO-1234yf is a 3-ton split-system air-conditioner and heat pump. While the charge limits are restrictive for large capacity split-system air-conditioners, the 3-ton configuration is likely to meet the 6.6 lbs limitation. Such a system has not been commercialized, nor is there published information available that documents the viability of the specific suggested design. The key question regarding technical readiness of the system is associated with the use of microchannel heat exchangers as the outdoor coils for heat pumps.

Table 1-9 below contains a list of the key components in the HFO-1234yf configuration.

Table 1-9: Key Components for HFO-1234yf Configuration

Components	Refrigerant System Specific Features
Heat Exchangers	Microchannel Evaporator, Microchannel Condenser
Compressor	Scroll or Rotary compressor
Expansion Device	2 Thermostatic expansion valves
Efficiency Enhancement Features	Suction-Line Heat Exchanger

Additional Refrigerant Cycle Features	Reversing valve to reverse refrigerant flow for heat pumping, Block valve connectors to connect tubing sections from the indoor and outdoor units, Refrigerant Charge Compensator, , Suction Line Accumulator

In summary, each refrigerant poses unique challenges that will require additional design features to address. Table 1-10 shows the additional design features that were included in each of the systems designs.

Table 1-10: Recommended Additions to Baseline Design for Each Refrigerant

Refrigerant	Configuration	Additional Design Features
Carbon Dioxide	Direct split-system	• Microchannel Evaporator and Condenser • Hermetic scroll expander/generator for work-recovery with power electronics and controls for conversion to 60Hz power while maintaining optimized high-side pressure • More complicated valve system to reverse refrigerant flow for heat pumping
Ammonia	Indirect	• Brazed-Plate Evaporator and Hydronic Indoor Coil to replace single Refrigerant/Air Indoor Coil • Microchannel Condenser • Steel Tubing for Ammonia circuit, copper or plastic tubing for glycol circuit • Water-Propylene Glycol loop serving Hydronic Air-Handler, Propylene Glycol Pump, Expansion Tank with Diaphragm
Propane	Direct room air conditioner	• System has a capacity of 0.34 RT; several air conditioners will be needed to meet full cooling and heating needs • Microchannel Evaporator and Condenser • All electrical components ignition-proof, separated from the main chamber, or located in an enclosure • Totally-enclosed air-over double-shafted motor
HFO-1234yf	Direct split-system	• System can reach a maximum capacity of 3.5RT; larger systems will require multiple circuits • Microchannel Evaporator and Condenser • Suction-Line Heat Exchanger • Block Valve Connectors

The information found in this report can be used in subsequent study to provide additional definition of the system and component design details to support development of cost estimates for the systems.

1. Introduction

As concerns about the global warming potential (GWP) of common fluorocarbon refrigerants have mounted in recent years, lower GWP refrigerants have garnered increasing attention. Among the options being evaluated are hydrocarbons like propane, ammonia, carbon dioxide (CO_2), and newly developed refrigerants like hydrofluoroolefins (HFOs). Industry is seeking alternative refrigerants which have low flammability as well as low GWP, combined with good thermodynamic efficiency and thermodynamic properties similar to those of conventional refrigerants. The high flammability associated with hydrocarbons makes them hazardous in most air conditioning applications. Carbon dioxide's thermodynamic cycle efficiency is lower than that of typical HFCs, and its properties are so different from fluorocarbons that they necessitate a complete and costly system redesign. Ammonia is a lower flammability refrigerant that is toxic and harmful to skin, eyes, and lungs. HFOs like HFO-1234yf are of particular interest due to their near zero GWP, similar properties to conventional fluorocarbon refrigerants such as R-134A and R-410A (used extensively for residential air conditioning).
In order to assess the viability of using candidate low-GWP refrigerants in ducted residential air conditioners and heat pumps, system configurations consistent with safety requirements and performance goals must be defined. Applicable codes and standards contain the relevant safety requirements. The costs and other relevant features of these system configurations (i.e. technical risk, suitability for the large replacement market, etc.) must be determined. This evaluation provides a first step towards completing such assessments by (a) identifying current applicable codes and standards that would dictate system design requirements, (b) development of the most attractive system configurations compliant with the applicable codes for four candidate low-GWP refrigerants, and (c) definition of system configuration design details.

The key performance goals for the system configurations include:

1) Suitable for use in both air-conditioning and heat pump applications.
2) Range of capacity consistent with conventional residential air conditioners, i.e. 1 to 5 tons.
3) Target efficiency comparable to current energy standards for residential central air conditioners and heat pumps, i.e. 13 SEER[1] for cooling performance and 7.7 HSPF.[2] This may not be feasible for some systems, and a full efficiency and feasibility analysis will require more research and development of this system and components.

The four candidate refrigerants considered in this work include propane, ammonia, carbon dioxide, and HFO-1234yf. All of these have low GWP, but some have potential drawbacks such as flammability, toxicity, potentially low efficiency, and/or operating conditions that are very different from those of conventional refrigerants.

The results of this study lead to the definition of key design details of the most promising system configurations for the candidate refrigerants. The information can be used in subsequent study to provide additional definition of the system and component design details to support development of cost estimates for the systems.

[1] Seasonal energy efficiency ratio
[2] Heating seasonal performance factor

The study included the three key tasks described below.

Task 1: Literature review

The tasks that were performed as part of Task 1 include:

- Review codes and standards that specify design requirements for residential air conditioning systems.
- Review published literature relevant to this performance assessment, to obtain information on existing design configurations and performance of direct expansion (DX) air-conditioning equipment using low-GWP alternative refrigerants.

Task 2: Evaluation of Candidate Systems

The tasks that were performed as part of Task 2 include:

- Evaluate and compare different system design configurations for the alternative refrigerants under consideration. Consider systems specifically for use of propane, ammonia, carbon dioxide, and HFO-1234yf refrigerants.

Task 3: Description of Selected System Configurations

The tasks that were performed as part of Task 3 include:

- Provide detailed descriptions of the best candidate system configuration for each of the alternative refrigerants under consideration, which will serve as a starting point for future design investigations.

2. Current State of Standards

2.1 Scope of the Search

The review of U.S. safety standards included technical standards that are published and maintained by engineering societies and organizations. These standards are often developed through consensus processes and are continually updated every 5 to 10 years. Only published standards were considered; draft versions may be subject to change during the development process. Key organizations include the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and Underwriter's Laboratories (UL).

The literature review looked at the Environmental Protection Agency's (EPA's) Significantly New Alternatives Policy (SNAP) requirements, but did not consider them when determining the final design configurations. None of the refrigerants under consideration in this study are approved for use for residential air conditioning under the SNAP Program. Hence, assessment of current requirements for these refrigerants would conclude that there would be no system configurations that are acceptable for use. However, for the purposes of this study we assume that achieving SNAP approval is a matter of formality, assuming other current codes are met by the proposed system configurations, and that submission of a complete application for SNAP approval by a manufacturer interested in selling such a system would lead to approval with limited delay. Hence, the study did not consider SNAP requirements in further analysis.

The literature did not include any reviews of international standards such as IEC or ISO standards, which may contain requirements that differ from or are not found in U.S. standards. We only considered standards which drive designs of U.S. equipment.

2.2 List of Applicable U.S. Standards

The following are standards and regulatory programs that influence the design of U.S. residential air conditioning equipment. While not all of these guidelines are mandatory for equipment, they collectively represent the current guidelines for acceptance of equipment using carbon dioxide, ammonia, propane, and HFO-1234yf.

In order to address the unique safety risks posed by flammable and toxic refrigerants, the majority of standards contain specific provisions that apply to A2, A3, B2, and B3 refrigerants. Special provisions may also apply to specific refrigerants, particularly ammonia. Note that current codes do not establish different requirements specifically for A2L refrigerants, for example HFO-1234yf. Such requirements are under discussion by various standards groups but have not yet been implemented in current standards. Hence, we treated HFO-1234yf as an A2 refrigerant for the purposes of this study.

Our previous report, "Review of Regulations and Standards for the Use of Refrigerants with GWP values less than 20 in HVAC&R Applications," provided an in-depth review of each current U.S. standard as it treats each refrigerant across many different applications. This report provides summaries of the relevant U.S. standards (current at the time of publication), highlighting the provisions of those standards that are relevant for the purposes of this study. Section 2.3 below summarizes the design requirements for the four refrigerants we addressed in this study as stipulated by these relevant standards for residential air-conditioning applications.

EPA Significantly New Alternatives Policy (SNAP) Program

EPA established the SNAP Program to evaluate and regulate substitutes for current Class I (CFC) and Class II (HCFC) ozone depleting refrigerants used in US industry. The EPA SNAP Program considers each refrigerant end use separately, including 16 different end uses for refrigeration and air conditioning.

At the end of an evaluation, EPA determines whether a particular refrigerant is deemed acceptable for use in a particular end use. Refrigerants can be deemed acceptable with certain restrictions on equipment design or installation. Use conditions and limits may include restrictions such as maximum charge size. The four listings that are available are the following:

- Acceptable
- Acceptable subject to use conditions
- Acceptable subject to narrowed use limits
- Unacceptable

Substitute refrigerants found to be unacceptable for a particular end-use cannot be used for that end-use in the US. Substitutes do not have to be considered risk-free to be considered acceptable, but should minimize risk during use. Substitutes are evaluated based on the following criteria:

- Atmospheric effects
- Exposure assessments
- Toxicity data Flammability
- Other environmental impacts

In the past, the EPA SNAP Program has granted certain users limited permission to test equipment using substitute refrigerants not considered acceptable for their particular end-use. The purpose of these waivers is to assess the risk of using the particular refrigerant.

As mentioned above, SNAP does not list any of the refrigerants of this study as acceptable for residential air conditioning applications, but we do not consider this in the assessment because it is expected that any serious application for approval that meets other applicable standards would likely be accepted.

ASHRAE Standard 15

ASHRAE Standard 15-2010 (“ASHRAE 15”) is published by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE). The purpose of the standard is to specify the safe design, construction, installation, and operation of refrigeration systems. The standard applies to all refrigeration and stationary air conditioning applications. Many building codes and bulletins look to harmonize with ASHRAE 15; for example, the International Mechanical Code incorporates most of the safety clauses for mechanical systems found in ASHRAE Standard 15. Refrigerants classified as mildly or highly flammable or as highly toxic in ASHRAE Standard 34, described below, receive restrictions on their use in ASHRAE 15.

The sections of ASHRAE 15 that are most relevant to specification of design requirements for the refrigerants considered in this study include the following:

1. Section 3 provides a definition for “self-contained” (equivalent to “unit”) system as being a complete, factory-assembled and factory-tested system that is shipped in one or more sections and has no refrigerant-containing parts that are joined in the field by other than companion or block valves. These types of valves allow isolation of the refrigerant in the separate sections when they are not connected, thus allowing installation and connection of separate components without field brazing or system charging.

2. Section 5.2 provides a definition for “high-probability” systems, which are those systems for which refrigerant that leaks from a failed component, tubing, or seal would likely enter the occupied space. This would apply for “direct” systems, in which the refrigerant is contained in components that directly condition the air of the occupied spaces, as is done in most conventional residential air conditioning systems in the U.S.

3. Section 7.2 indicates that potential refrigerant concentrations in case of release shall be within the limits of ASHRAE Standard 34 Tables 1 and 2.

4. Section 7.3 provides guidelines for calculating the volume associated with the potential refrigerant concentrations in case of release.

5. Section 7.5.2 indicates that refrigerants of Groups A2, A3, B1, B2, and B3 shall not be used in high probability systems for human comfort, but indicates that there are exceptions to this restriction, in particular for unit systems with refrigerant charges no more than those listed in Table 1 of the standard. For residential occupancy, the charge limit listed in Table 1 is 6.6 lbs (3 kg).

6. Section 7.5.3 indicates that flammable refrigerants of Groups A3 and B3 shall not be used unless allowed by the Authority Having Jurisdiction, meaning an authority such as a building inspector. This section also allows three exceptions, including use of portable-unit systems containing no more than 0.331 lbs (150 g) of Group A3 refrigerant. While some building inspectors may approve use of equipment with flammable refrigerant, it is not reasonable to expect that inspectors would generally make such an exception. Hence, this requirement effectively bans use of B3 refrigerants and limits use of A3 refrigerants in residences to portable-unit systems (e.g. room air conditioners) with the aforementioned charge limits.

<u>ASHRAE Standard 34</u>

ASHRAE Standard 34-2010 (“ASHRAE 34”) is published by ASHRAE. The purpose of the standard is to provide a system for referencing refrigerants and classifying refrigerants based on toxicity and flammability. The different safety classifications developed in ASHRAE 34 are used in ASHRAE 15 to provide safety guidelines for the design and installation of refrigerating systems, based on the refrigerant that is used. In addition, ASHRAE 34 defines the permissible concentration limits allowed by ASHRAE 15.

The sections of ASHRAE 34 that are most relevant to specification of design requirements for the refrigerants considered in this study include the following.

1. Safety classifications, as defined for individual refrigerants using toxicity and flammability groups. The classifications are summarized in the figure below.
   - Based on the lower flammability limit (LFL) and heat combustion of the refrigerant, a refrigerant can be classified as either class 1 (no flame propagation), 2 (lower flammability) or 3 (higher flammability). Class 2 refrigerants with a maximum burning velocity of 10 cm/s can also be designated as 2L.
   - Based on the permissible exposure level (PEL) and occupational exposure limit (OEL) of the refrigerant, a refrigerant can be classified as either class A (lower toxicity) or class B (higher toxicity).

Refrigerant Safety Groups – ASHRAE Standard 34-2010

Higher Flammability	A3	B3
Lower Flammability	A2	B2
	A2L*	B2L*
No Flame Propagation	A1	B1
	Lower Toxicity	Higher Toxicity

** A2L and B2L are lower flammability refrigerants with a maximum burning velocity of ≤ 10 cm/s*

Figure 2-1: Refrigerant safety groupings in ASHRAE Standard 34-2010

2. Refrigerant Concentration Limit (RCL) as the maximum allowable concentration limits of the refrigerant in air in order to reduce the risks of acute toxicity, asphyxiation, and flammability hazards in normally occupied, enclosed spaces.

   Table 2-1 below lists the refrigerant concentration limits for each of the candidate refrigerants and two currently used refrigerants.

Table 2-1: RCL Limits from ASHRAE 34

Refrigerant	RCL (lbs/Mcf)
Carbon Dioxide	4.5
Ammonia	0.014
Propane	0.56
HFO-1234yf	4.7
R-410A	25
R-134A	13

3. Section 7.1 and subsections 7.1.1 through 7.1.3 provide requirements for determination of RCL for single-component refrigerants, such as the refrigerants under consideration in this study. Concentration limits are determined based on toxic effects, oxygen deprivation, and flammability—the lowest of these limits takes precedent.

4. Tables 1 and 2 in the standard provide RCLs for single-component and blend refrigerants.

International Residential Code, International Mechanical Code, and Uniform Mechanical Code

The International Residential Code for One- and Two-Family Dwellings (IRC) compiles all building, plumbing, mechanical, fuel gas and electrical requirements for one- and two-family dwellings in one convenient code. The regulations cover dwellings and townhouses up to three stories. The IRC has been adopted by the vast majority of localities as their official residential building code, with and without amendments. The IRC requires that all equipment must be UL-listed. Hence, the significance of the IRC to this study is that it establishes that equipment used in residences shall meet requirements developed and codified in UL standards.

The International Building Code (IBC) provides standards for the construction, alteration, movement, enlargement, replacement, repair, equipment, use and occupancy, location, maintenance, removal, and demolition of every building or structure. The International Code Council publishes the IBC and updates it every three years. The latest version of the IBC code is IBC 2009, but many state building codes reference the older 2006 and 2003 versions. The IBC has been adopted by the vast majority of states as their official building code, with and without amendments. The IBC defers to the International Mechanical Code for standards on HVAC&R equipment.

The International Mechanical Code (IMC) provides safety regulations for the design, installation, construction, and repair of refrigeration systems that vaporize and liquefy a fluid during the refrigerating cycle. The International Code Council publishes the IMC and updates it every three years. The IMC draws many of its regulatory requirements from ASHRAE Standard 15, though it does deviate from the standard in some places. The IMC is referenced by the IBC as the regulatory source for mechanical systems. The latest version of the IMC code is IMC 2009, but many state mechanical codes reference the older 2006 and 2003 versions. The IMC has been adopted by nearly three-quarters of the states as their official mechanical code, with and without amendments. The IMC provides the same function as the Uniform Mechanical Code, and states can adopt either code.

The IBC and IMC generally would not supersede the IRC in mandating requirements for equipment used in residences. However, they establish requirements that are for the most part identical to ASHRAE Standard 15 to address equipment containing refrigerants.

Underwriter's Laboratories (UL) Standards

UL 484 (8^{th} Edition)

UL Standard 484 covers safety standards for room air conditioners, including packaged terminal air conditioners, special purpose air conditioners, and recreational vehicle air conditioners. This standard provides additional requirements for room air conditioners using a flammable refrigerant.

UL 984 (7th Edition)

UL Standard 984 covers safety standards for hermetic refrigerant motor-compressors, rated 7200V or less, used in both air conditioning and refrigerating equipment.

UL 1995 (4rth Edition)

UL Standard 1995 covers safety standards for a variety of stationary heating and cooling equipment, including heat pumps, air conditioners, combination heating and cooling equipment, liquid chillers, and condensing units. This equipment is intended for use in nonhazardous locations, rated 7200 V or less, single- or 3-phase.

UL Standard 1995 does not contain separate requirements for flammable refrigerants. As such, the current requirements in UL 1995 do not represent the full requirements that are required for equipment seeking UL listings with flammable refrigerants. For equipment using flammable refrigerants to be listed by UL, new requirements will have to be created.

2.3 *Summary of Guidelines for Alternative Refrigerants*

The sections below summarize the main safety requirements for each refrigerant, as contained within each of the standards considered in section 2.2 of this report.

<u>Carbon Dioxide</u>

According to the safety requirements provided in ASHRAE 15 and UL 1995, carbon dioxide systems are not limited in charge size or in their design. However, carbon dioxide systems must meet general strength requirements for all refrigerant-containing parts, requirements that are more restrictive for carbon dioxide due to the relatively high pressures of a transcritical carbon dioxide system.

UL Standard 1995 requires that all refrigerant-containing components be able to withstand test pressures (using the strength test in Section 61 of UL 1995) that are:

1. Five times the maximum normal working pressure
2. Three times the maximum abnormal pressure
3. Five times the minimum design pressures

UL 1995 does allow for an exception to the design pressures above, to systems that can withstand a fatigue test (in accordance to Section 61A of UL 1995) using the following test pressures:

1. Three times the maximum normal working pressure;
2. Three times the maximum abnormal pressure developed; or
3. Three times the saturation pressure of the refrigerant at:
    a. 80˚ F (for equipment on the low-side)
    b. 125˚ F (for equipment on the high-side)

Carbon dioxide has not been approved by the EPA SNAP program for use in residential air-conditioning systems.

Table 2-2 below contains a summary of all relevant requirements.

Table 2-2: Standard Requirements for Carbon Dioxide

Requirements	Source of Requirement
Strength requirements for pressure	UL 1995

Ammonia

According to the safety requirements provided in ASHRAE 15 and ASHRAE 34, and UL 1995, use of ammonia is very restricted in direct systems and not restricted in indirect systems.

ASHRAE 34 sets an RCL of 0.014 lbs/mcf for ammonia. In the best-case scenario, in which the entire volume of a house can be considered for refrigerant dispersion, this would limit the charge for a system serving a 1,700 sq. ft. house with 8-foot ceilings to 0.2 lbs, or 87 g. The 1,700 sq. ft. house size was the median for existing single detached and manufactured homes in the Census Bureau's 2009 Housing Survey.[3]

Providing the required cooling capacity in a direct split-system configuration generally requires a number of pounds of refrigerant in conventional systems (typically 6 to 10 lbs in R-410A systems[4]). Less refrigerant charge may be required in a system using microchannel heat exchangers, but available information suggests that 0.2 lbs is not sufficient. Work by Hrnjak et al. showed that a 3.7-ton ammonia chiller with microchannel heat exchangers used 240 g of ammonia refrigerant, including 120 g in the microchannel condenser[5]. Assuming that charge is proportional to capacity and the 65g/ton ratio of this example, the 0.2 lbs (87 g) limit may be sufficient for 1.3 tons capacity, but this would not account for charge increases due to heat pumping features and additional piping into the residence (the liquid line piping in particular will add significantly more charge), nor the possibility that the volume to be considered for refrigerant dispersion would be limited by doors closing off parts of the residence.

UL Standard 1995 requires that all refrigerant-containing parts be resistant to corrosion. This will influence design of ammonia systems, as ammonia is highly corrosive to copper tubing.

Ammonia has not been approved by the EPA SNAP program for use in residential air-conditioning systems.

Table 2-3 below contains a summary of all relevant requirements.

[3] "American Housing Survey for the United States: 2009", U.S. Department of Housing and Urban Development, Issued March 2009, Table 1-3, http://www.census.gov/prod/2011pubs/h150-09.pdf

[4] Ingram's Water and Air Equipment. "Installation and Operation Manual". Central Air Conditioner. Models: HC18-60A1VAR/S, HC18-60C1VAR, HC18-60D1VAR." http://ingramswaterandair.com/

[5] Hrnjak, P. et al. "Microchannel heat exchangers for charge minimization in air-cooled ammonia condensers and chillers." University of Illinois at Urbana-Champaign. January 2008.

Table 2-3: Standard Requirements for Ammonia

Requirements	Source of Requirement
6.6 lbs charge restriction in (direct) unit systems	ASHRAE 15
Heavily restrictive RCL limit of 0.014 lbs/mcf in high probability systems	ASHRAE 34 and 15
No copper or copper-containing alloys in contact with ammonia refrigerant	ASHRAE 15, UL 1995

Propane

According to the safety requirements provided by ASHRAE 15, UL 1995 and UL 484, use of propane is highly restricted.

ASHRAE Standard 15 does not allow the use of A3 refrigerants in configurations other than portable-unit systems (portable and complete, factory-assembled and factory-tested systems) containing up to 150g of refrigerant. UL Standard 484 allows certain charge sizes based on the LFL of the refrigerant; for example, up to 150g of propane in room air conditioners[6] without restriction (consistent with ASHRAE Standard 15 requirements) and up to 1 kg of propane with charge restrictions based on room size. The ASHRAE charge restriction is intended to apply to individual refrigerant circuits within the appliance, while the UL Standard 484 charge restriction amounts apply to the total amount of charge used in the appliance. The ASHRAE Standard 15 restriction effectively precludes consideration of the larger charge allowances of UL Standard 484.

UL Standard 484 notes that, for equipment using flammable refrigerants, electrical components that are potential ignition sources during normal operation or a leak must either:

- Be ignition-proof
- Be separated from the likely leak area
- Be located in a separate enclosure suitable for the refrigerant used

UL Standard 484 also notes that the appliance should be able to withstand a drop with either the bottom or any one of the sides pointed downwards. Table 2-4 below contains the drop heights that the individual appliance must withstand.

Table 2-4: UL 484 Drop Test Heights for Equipment using Flammable Refrigerants

Appliance weight, kg	Drop height, cm
<10	20
>= 10 and <20	17
>= 20 and <30	15
>= 30 and <40	12
>= 40	10
Source: UL 484	

[6] UL Standard 484 defines a room air conditioner as a “factory-made encased assembly […] intended for installation in a window, through a wall, or as a console located in or adjacent to the room, zone, or space to be conditioned.” Source: UL Standard 484 (1998).

Propane has not been approved by the EPA SNAP program for use in residential air-conditioning systems.

Table 2-5 below contains a summary of all relevant requirements.

Table 2-5: Standard Requirements for Propane

Requirements	Source of Requirement
Restriction of design to room air conditioner systems with no more than 150g charge	ASHRAE 15
Electrical Equipment Requirements	UL 484
Ability to resist drop test	UL 484

<u>HFO-1234yf</u>

According to the safety requirements provided in ASHRAE Standard 15 and UL 1995, use of HFO-1234yf is somewhat restricted in direct systems and not restricted in indirect systems.
ASHRAE Standard 15 restricts A2 systems using direct configurations to unit systems using no more than 6.6 lbs of charge. The direct equipment must be a factory-assembled product that requires no brazing of refrigerant parts in the field. A2 refrigerants are also restricted to no more than 1100 lbs within an occupancy setting, in combination with any B2, A3, and B3 refrigerants, but this requirement is not likely to be applicable for residential air conditioning systems, which would not have such high charge levels.

HFO-1234yf has not been approved by the EPA SNAP program for use in residential air-conditioning systems.

Table 2-6 below contains a summary of all relevant requirements.

Table 2-6: Standard Requirements for HFO-1234yf

Requirements	Source of Requirement
6.6 lbs charge restriction in (direct) unit systems	ASHRAE 15

3. Selection of Equipment Configurations

After reviewing the requirements contained within the standards for each refrigerant, we selected the best configuration for each refrigerant as the basis for detailed equipment descriptions. We considered requirements from all applicable U.S. safety standards, addressing ambiguities as described in Section 3.1 below. We then considered several potential configurations, and selected one based on its fit with current standard requirements and the attractiveness of the configuration in terms of cost and efficiency.

Sections 3.1, 3.2, and 3.3 below describe the elements of the configuration selection process.

3.1 Lack of Requirements in UL Standard 1995

When defining equipment configurations for each candidate refrigerant, we considered the requirements in current U.S. standards. However, by the publication of this report, UL requirements had not been developed for use of flammable refrigerants in all air conditioning applications. While some UL standards like UL standard 250 and UL standard 484 have specific requirements for equipment using flammable refrigerants, UL Standard 1995 currently does not have specific requirements for flammable refrigerants. While this would not specifically ban the use of these refrigerants in air-conditioning equipment, it does mean that UL must develop requirements in the future to list this equipment.

Because UL 1995 does not provide specific requirements for flammable refrigerants, we used the requirements in ASHRAE Standard 15 as a model for potential revisions to UL 1995. For equipment using flammable refrigerants in configurations covered by UL Standard 1995, we assumed no further requirements beyond those in ASHRAE Standard 15.

3.2 Possible Configurations

Equipment configurations can be separated into two categories: direct systems and indirect systems. Standards such as ASHRAE Standard 15 contain separate provisions for each kind of system.

<u>Direct</u>
A direct system contains one refrigerant loop which is in contact with both the occupied space and the outdoor space.

In the U.S. market, the most common equipment configuration for residential air-conditioning is a direct split-system. A direct split-system configuration includes an indoor unit with an evaporator (or indoor coil in the case of a heat pump) within the occupied space and a condensing unit with a condenser (or outdoor coil in the case of a heat pump) in the outdoor space. The two units are connected through refrigerant lines that complete the refrigerant circuit. Air cooled by the evaporator is circulated in ductwork to the air-conditioned rooms.

Single-packaged systems are also used but are not as common. One example of single-packaged systems are room air conditioners, which contain one refrigerant loop and are installed in a window, in order to have contact with both the occupied space and the outdoor space. Another example would be a single-packaged system that connects to a duct network.

Indirect

An indirect system isolates the primary refrigerant from the occupied space. The primary refrigerant is contained within a refrigerant loop that is completely located in the outdoor space. It transfers heat to a secondary fluid, which is in a loop that is in contact with the occupied space. In this configuration, the primary refrigerant is never in contact with the occupied space.

A typical indirect configuration would be a residential chiller serving a hydronic air handing unit. It would have an air-handler with a cooling coil in the occupied space; the cooling coil would be cooled with a secondary refrigerant such as a propylene glycol-water solution (a propylene glycol solution would be used to avoid freezing during winter). The secondary refrigerant would flow through tubing to an outdoor unit (i.e. a chiller), where it would be cooled in an intermediate heat exchanger that is cooled by the primary refrigerant loop.

3.3 Selection of Configurations

For each candidate refrigerant, we selected one of the following configurations for further study.

- Direct split-system
- Direct room air conditioner system
- Indirect

Of these three possible configurations, we consider direct split-systems to be the best choice because it avoids the potential efficiency reduction and added cost associated with an indirect configuration, and is most compatible with current systems. Room air conditioner systems are not compatible with the majority of the U.S. market, and are otherwise considered a compromise approach due to aesthetic reasons and the need to install numerous units for proper distribution of cooling. Indirect systems add several levels of cost associated with the additional heat exchanger and the propylene glycol circulating system. The need for transfer of heat in the intermediate heat exchanger and the added power input of the pump also make achieving equivalent efficiency more difficult for indirect systems without resorting to design adjustments such as larger heat exchangers, which in turn lead to further cost increase. When possible, we selected a direct split-system as the configuration of choice. When a direct split-system was not selected, it was due to the requirements of safety standards identified in Section 2.3 of this report.

Table 3-1 below shows the equipment configurations selected for each candidate refrigerant, along with a justification for the selection.

Table 3-1: Selected Configurations for All Refrigerants

Refrigerant	Configuration	Justification
Carbon Dioxide	Direct split-system	No restriction on use of direct split-systems, which offer the best choice of efficiency, cost, and compatibility with current systems.
Ammonia	Indirect	RCL limits for ammonia in ASHRAE 34 make direct configurations impractical.
Propane	Direct room air conditioner	Safety standards limit the potential configurations to direct room air conditioner configurations.
HFO-1234yf	Direct split-system	Some restriction on use of direct split-systems, based on charge limits, but preliminary analysis shows that this issue can be addressed using design approaches that minimize charge. Direct split-systems offer the best choice of efficiency, cost, and compatibility with current systems.

Section 4 of this report describes the configuration for each refrigerant in detail.

4. Equipment Configurations

The sections below describe the selected configurations for each of the candidate refrigerants.

4.1 Carbon Dioxide

The sections below describe our configuration for carbon dioxide. Our selected configuration for carbon dioxide is a 3-ton split-system air-conditioner and heat pump. The proposed system meets all of the code requirements listed in Section 2.3 above.

Carbon dioxide systems must use transcritical cycles, because the critical temperature of carbon dioxide is 88˚ F (31˚ C), which is insufficient to meet air-conditioning and heat pump operating conditions. High throttling loss during the expansion process reduces the efficiency of transcritical carbon dioxide systems (Huff, Hans-Joachim and Radermacher, Reinhard, 2003). Hence, a key consideration for design of a carbon dioxide system is achieving target efficiency levels. At a minimum, such a system would be expected to meet U.S. Department of Energy efficiency regulations, which currently require air conditioners to achieve a SEER level of 13.0 Btu/h-W and heat pumps to achieve a SEER of 13.0 Btu/h-W and HSPH of 7.7 Btu/h-W (unless they are through-the-wall or space-constrained units).[7] However, manufacturers generally offer air conditioners and heat pumps that span a wide range of efficiencies extending significantly higher than these levels.

In order to address the efficiency challenges associated with carbon dioxide, heat exchanger performance improvement including increase of heat exchanger size could be considered at a baseline efficiency level. However, such an approach would not likely be feasible across the range of efficiency levels of current product offerings. Hence, the target efficiency for a carbon dioxide system would be the same as that of a conventional R-410A system without allowing significant increase in size of the system components. Our proposed system is intended to represent the most likely design path to reach this goal, but it is not certain, based on publicly available information, whether it would.

To help mitigate the gap in efficiency, the proposed system will use a work-recovery expander instead of a thermostatic expansion valve to reduce the losses associated with the throttling expansion used in most conventional systems. Theoretical studies have shown that, when integrating a work-recovery expander in the cycle, the carbon dioxide systems can approach the efficiency of R-410A systems. For example, theoretical computer modeling studies showed that an expander of 80% efficiency allows carbon dioxide to achieve a similar efficiency to R-22 at 97˚ F (36˚ C), and a better efficiency at lower outdoor temperatures, without additional changes to the system (Huff, Hans-Joachim and Radermacher, Reinhard, 2003).

Published test results of operating carbon dioxide expanders have not yet shown that such expansion efficiency levels have been attained. Even with further development, our proposed non-integrated expander design will likely not achieve an expander efficiency of 80%, and our design took a more conservative estimate of the expander-generator's efficiency. Achieving full parity may require

[7] U.S. Code of Federal Regulations, Title 10, Part 430, Section 32(c)(2).

additional design changes to increase the heat exchanger and/or compressor efficiencies. Furthermore, accurate prediction of carbon dioxide system performance would require a more thorough analysis than was completed as part of this study, including careful evaluation of heat exchanger performance. A full efficiency and feasibility analysis will require more research and development of this system and components.

While there are no known prototypes for a dual cooling and heating carbon dioxide heat pump, heat pump operation could be achieved using valves to reverse the flow. Unlike in conventional air conditioning systems, this is more complicated in a system using a work-recovery expander. This issue and a suggested approach to address it are discussed in more detail below.

The sections below describe:

- The key design parameters used to design the system and size the components
- The physical positioning of all relevant components and sections
- The components that are used by this system

4.1.1 Key Design Parameters

Table 4-1 below contains the key design parameters for the carbon dioxide air-conditioning system. These design parameters will guide the sizing of the key components and any relevant safety features. The charge size was calculated based on a typical 8.4 lbs charge of a 3-ton R-410A system, adjusted for the ratio of volumetric capacities between the refrigerant and a 40% refrigerant charge savings when going from round-tube to microchannel heat exchangers (Ingram's Water and Air Equipment).

Table 4-1: Carbon Dioxide System Design Parameters

Design Parameters	Value
Capacity	3 RT
Target Efficiency	13 SEER; 7.7 HSPF[1]
System-type	Direct split-system with indoor and outdoor units
Applicable Standards	ASHRAE 15, UL 1995
Refrigerant Charge	5.5 lbs
Design Requirements	Design for High Pressures, Enhancements to Address Low Efficiency of Simple Carbon Dioxide Cycles
High Pressure Mitigation	Increased tube wall/diameter ratio
Low-Efficiency Mitigation	Work-Recovery Expander with Generator

[1]: Due to the low technical readiness of the design options discussed, further research and development may be required to establish the viability of the work-recovery expander design.

While the details in this section apply specifically to a 3-ton air-conditioning system, there are no barriers to prevent this configuration from being used in larger systems, such as a 5-ton air-conditioning system.

4.1.2 Layout

Figure 4-1 below shows a schematic of the full refrigeration system and the carbon dioxide's relation to the occupied space. The A1 ASHRAE rating of the refrigerant allows the refrigeration system to be placed in direct contact with the indoor space.

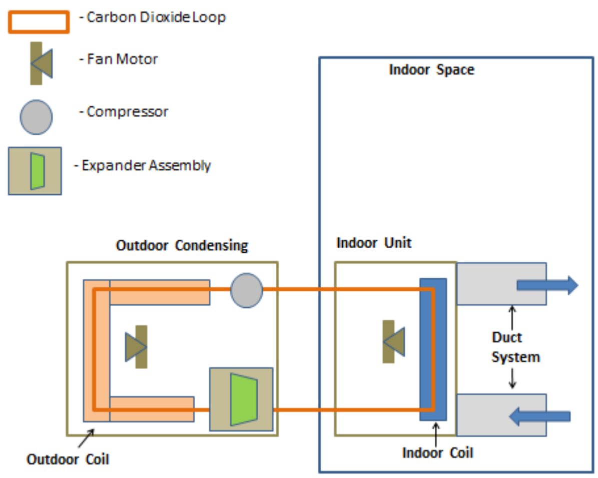

Figure 4-1: Layout of the Full Carbon Dioxide System

4.1.3 Key Components

Table 4-2 below contains a list of key system components. Detailed descriptions of the heat exchangers, compressor, and expander follow the table.

Table 4-2: Carbon Dioxide System Key Components

Components	Refrigerant System Specific Features
Heat Exchangers	Microchannel Indoor Coil, Microchannel Outdoor Coil
Compressor	Hermetic 3-ton rotary compressor
Expansion Device	Hermetic scroll expander/generator for work-recovery with power electronics and controls for conversion to 60Hz power while maintaining optimized high-side pressure.[1]
Additional Refrigerant Cycle Features	Reversing valves to reverse refrigerant flow for heat pumping, Refrigerant Charge Compensator, Suction Line Accumulator

[1]: Expander efficiency in the range of 60-70% would likely be required to approach parity with conventional HFC systems.

Heat Exchangers

Microchannel heat exchangers offer advantages for carbon dioxide systems over round-tube configurations, including:

- Smaller diameter tubes in microchannel can withstand higher operating pressures
- Lower viscosity in carbon dioxide allows for higher mass-flow rates in microchannel and more tolerance for pressure drops
- Equivalent heat transfer performance in a more compact size

However, Padhmanabhan, Sankar et al. noted that microchannel heat exchangers experienced more frequent frosting and greater performance impacts in frosting conditions, due to imperfect defrosting performance. These heat exchangers may require further development to assure their viability for use in as outdoor heat exchangers for heat pumps. It may be necessary instead to use conventional round-tube heat exchangers in the carbon dioxide system, in which case the heat exchanger size and system size may have to increase in order to achieve comparable efficiency levels.

Table 4-3 below contains specifications for the two heat exchangers in this system. The heat exchanger details were developed based on the following considerations:

- The heat exchanger face areas are equivalent to those in a typical R-410A split-system (DOE CAC TSD).
- The heat exchanger depth, tube diameter, and fins per inch are based on a microchannel prototypical air conditioner using carbon dioxide (Zhao, Y. et al).
- The fan motor sizes are equivalent to those of a typical R-410A split-system (DOE CAC TSD). Because of the reduced pressure drop associated with the microchannel heat exchangers, the fan motor sizes could potentially be reduced by 5-10%.

Table 4-3: Carbon Dioxide System Heat Exchangers

Characteristic	Outdoor Coil	Indoor Coil
Type of Heat Exchanger	Microchannel	Microchannel
Material	Aluminum	Aluminum
Configuration	Air/Refrigerant	Air/Refrigerant
Capacity	Sized for a 3-ton heat pump unit	
Channel Diameter	0.04 inches	0.04 inches
Face Area	3024 sq. inches[1]	1152 sq. inches[1]
Depth	0.6inches	0.6 inches
Fins Per Inch	16	16
Fan Motor Sizes	0.25 HP	0.45 HP

Source: Zhao, Y. et al
[1]: The face area was assumed to be equivalent to a typical R-410A system, as described in the DOE CAC TSD.

Heat exchanger designs must account for the high operating pressures within the carbon dioxide transcritical cycle to meet current safety standards. The safety requirements listed in Section 2.3 of this report note that the components must pass either strength tests using test pressures of 5 times the operating pressure or fatigue tests using test pressure of 3 times the operating pressure. Tests of one set of prototypical carbon dioxide microchannel heat exchangers used high-side test conditions of up to 12.5 MPa in order to meet outdoor conditions of up to 95˚ F (Zhao, Y. et al, 2011); the burst pressure would thereby have to be at least 62.5 MPa for the strength tests, or 37.5 MPa for the fatigue tests. Furthermore, design for 95 ˚F ambient does not sufficiently address design conditions for U.S. localities, and even higher pressures could be required.

The literature review did not provide sufficient information to allow confident prediction of the likely burst pressures of tested prototypes (and hence the safety factors applicable for these designs), nor regarding the design details required to achieve the UL-mandated safety factors for expected design operating conditions. Zhao, Y. et al, 2011 used headers with a 0.14 inch thickness and a 0.83 inch outer diameter; and microchannel tubes with a diameter of 0.04 inches. However, ultimate strength of these heat exchanger designs was not reported.

Design of the microchannel tubes and the tubes used to transfer refrigerant between components to withstand the required pressure levels (i.e. up to at least 62.5 MPa) is relatively straightforward because tube wall hoop stress can be readily estimated for these configurations. Design of the interface between the header and the microchannel tubes is much more complicated, and it is this part of the heat exchangers that is generally weakest. This portion of the design may require implementation of manufacturing techniques to meet the safety requirements that could increase the cost of the heat exchangers, as compared with microchannel heat exchangers designed for conventional refrigerants. As the literature provides no guidance regarding design details or cost, defining this part of the design and projecting its cost would require more in-depth engineering analysis than has been conducted in this study.

<u>Carbon Dioxide Compressor</u>

Several carbon dioxide compressors are available as either prototypes or commercial products. Sanyo Electric Co. Ltd. developed two-stage rotary carbon dioxide compressors (Sanyo), and researchers have developed several scroll prototypes (Holloway, Seth et al.). These compressors incorporate brushless DC motors and are resistant to high working pressures.

<u>Scroll Expander</u>

Several prototype scroll expanders have been developed, and recent prototypes have achieved total efficiencies of 55% (Fukuta, Mitsuhiro et al., 2006). The scroll expanders use scroll elements from scroll compressors.

While integrated compressor-expander systems have been theorized and studied through simulation, and prototype units have been built and tested, these systems have not been fully developed to commercialization. It is not clear that concerns about displacement match for performance optimization over a wide range of operating conditions have been resolved, particularly for both air conditioning and heat pumping operation. A more conservative approach would study a non-integrated system that connects the expander to a generator and power electronics. This configuration would produce energy that can offset power consumption by other components (Huff, Hans-Joachim and Radermacher, Reinhard). While this configuration would be more costly and less efficient than compressor/expander integration, it would have greater flexibility to assure proper system performance in all operating modes. We have adopted this conservative approach for our carbon dioxide system.

A non-integrated system would involve use of a hermetic package housing the scroll expander and the generator. Power electronics would be used to convert generated power into 60 Hz line power, while varying the rotation speed to ensure optimal efficiency of the refrigeration system. However, no such expander/generator is currently available commercially, prototype heat pump systems successfully using such a device have not been discussed in the open literature, and questions remain regarding the peak efficiency levels achievable by such a device. The expander would likely have a lubrication system with a small oil sump. System design would have to consider how to assure that neither the compressor nor expander run out of oil. The system would also include the necessary solenoid valves and piping for connections to the main refrigerant circuit both for cooling and in reverse mode for heat pump operation.

There are some challenges associated with integrating the expander into a system designed for both air-conditioning and heat pumping. Typical heat pump systems use two thermostatic expansion valves (TXV's), but use of two expander/generator assemblies would be prohibitively expensive. Thus, a single expander would be used--placement of the expander in the outdoor assembly was chosen for the following reasons:

- Due to the difference in operating temperatures between the heat pump and air-conditioning modes, and to the expectation that more of the interconnecting refrigerant piping is located inside the house, placement of the expander in the outdoor coil is expected to result in less significant thermal loss associated with two-phase refrigerant flow through one of the interconnecting refrigerant lines when the operating evaporator is not in the package housing the expander (i.e. if the expander is located in the outdoor unit, the two-phase refrigerant will flow through the interconnecting tubing in cooling mode).
- The outdoor assembly has more space to accommodate the expander assembly
- Placement of the expander in the outdoor assembly close to the compressor will allow for future integration of the expander and compressor components

Exact details of all circuiting of the expander with the refrigeration system using solenoid valves will need to be developed; we have made a conservative estimate of four solenoid valves for the valve requirements. Previous studies of carbon dioxide units with expanders showed that two valves are likely needed to control the entry and exit of the refrigerant into the expander (Baek, Joo Seok, et al.). Two more valves may be required to control the circuiting of refrigerant when system operation is reversed, to ensure proper operation of the expander.

Heat Pump Features

A reversing valve (at the compressor inlet), a refrigerant charge compensator, and a suction line accumulator are included in the design to allow for heat pump operation of the cycle. The reversing valve allows for the compressor to change the direction of the suction and discharge lines. The refrigerant charge compensator will balance the refrigerant charge differences for air-conditioning mode versus heat pump mode by storing refrigerant charge. The suction line accumulator will prevent liquid slugs from damaging the compressor, during cold start.

In addition, reverse operation of the scroll expander may require additional valves, as mentioned in the section above.

4.1.4 Sources

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Padhmanabhan, Sankar et al. "Comparison of Frost and Defrost Performance between Microchannel Coil and Fin-and-Tube Coil for Heat Pump Systems." Purdue University Purdue e-Pubs. http://docs.lib.purdue.edu/iracc/869/

4.2 *Ammonia*

The sections below describe our configuration for ammonia. The selected configuration for ammonia is a 3-ton heat-pump chiller system. The target efficiency for a fully developed ammonia system would be the same as a conventional R-410A system. Our proposed system is intended to lay out a design path to reach this goal. With this system, the ammonia will act as the primary refrigerant for the chiller/heater, which will be located outdoors. The primary refrigerant will heat or cool the water-propylene glycol mixture secondary refrigerant, which flow in a loop that runs between the outdoor section and an indoor hydronic fan-coil unit. The system meets all of the code requirements listed in Section 2.3 above, and is considered a low-probability system under ASHRAE 15.

The heat-pump chiller configuration is best suited to meet the RCL requirements for ammonia in ASHRAE Standards 15 and 34, which are much lower than those for other candidate refrigerants. The chiller configuration is intrinsically about 10% less efficient than a comparable split-system due to the additional temperature lift the refrigeration system must overcome to transfer heating or cooling to the secondary refrigerant, and the power input for the pump required to circulate the secondary refrigerant.[8]

The reduced efficiency associated with the indirect configuration will be mitigated due to the increased efficiency of the ammonia cycle. Under identical operating conditions ammonia is about 10% more efficient than conventional refrigerants such as HCFC-22 (Inlow, S.W. and Groll, E.A.) and HFC-410A (Digmanese). Thus the penalty for an indirect system would be wholly or partially mitigated. A full efficiency and feasibility analysis will require more detailed analysis than was completed for this study.

The complete heat-pump chiller configuration includes a secondary water- propylene glycol loop that runs between a brazed heat exchanger (transferring heat from the ammonia loop) and an indoor hydronic heat exchanger (which is connected to a duct system for air delivery). Designs of commercial R-410A heat-pump chiller systems were used as guides for the design of this configuration.

The sections below describe:

- The key design parameters used to design the system and size the components
- The physical positioning of all relevant components and sections
- The components that are used by this system

4.2.1 Key Design Parameters

Table 4-4 below contains the key design parameters for the ammonia air-conditioning system. These design parameters will guide the sizing of the key components and any relevant safety features. The ammonia refrigerant charge is based on an ammonia chiller prototype developed by Hrnjak, P. et al. that achieved a ratio of 18g of charge per kW of cooling using microchannel heat exchangers.

[8] A 60,000 Btu/h heat-pump chiller system may use a 0.5 HP pump for the primary water- propylene glycol system (Multi aqua). A pump half this size (0.25 HP) would represent 5% of the power required for a 36,000 Btu/h, 10 EER system. An additional 5% loss is due to the heat losses through the additional heat exchanger and secondary loop.

Table 4-4: Design Parameters for Ammonia System

Design Parameters	Value
Capacity	3 RT
Target Efficiency	13 SEER; 7.7 HSPF
System-type	Indirect Chiller with a water- propylene glycol loop
Applicable Standards	ASHRAE 15, UL 1995
Ammonia Refrigerant Charge	190 g
Design Requirements	Indirect System Design
Indirect Implementation	Water-Propylene Glycol Loop, Brazed Plate Heat Exchanger

While the details in this section of the report are specifically designed for a 3-ton air-conditioning system, there are no barriers to prevent this configuration from being used in larger systems, such as a 5-ton air-conditioning system.

4.2.2 Layout

Figure 4-2 below contains a picture of an R-407C outdoor chiller assembly. This chiller is typically used in light commercial applications with loads of 5 RT (Multi aqua). It delivers both heating and cooling by using a reversing valve. Elements from this chiller were used to inform our ammonia configuration.

Figure 4-2: Picture of a 5 RT Light-Commercial Chiller Outdoor Unit

Source: Multi aqua

Figure 4-3 below shows a schematic of the full refrigeration system and the ammonia's relation to the occupied space. The figure shows that the ammonia loop is kept outside the indoor space, allowing it to comply with current safety standards as an indirect system.

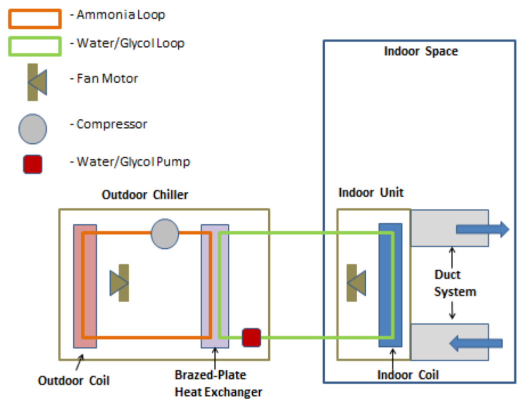

Figure 4-3: Layout of the Full Ammonia System

4.2.3 Key Components

Table 4-5 below contains a list of key system components. Detailed descriptions of the heat exchangers, propylene glycol loop, and compressor follow the table.

Table 4-5: Ammonia System Key Components

Components	Refrigerant System Specific Features
Heat Exchangers	Brazed-Plate "Indoor" Heat Exchanger, Microchannel Outdoor Coil, Hydronic Air Handler
Compressor	Hermetic ammonia scroll compressor
Expansion Device	2 Bi-Directional Expansion/Check Valves
Connective Tubing	Steel Tubing for Ammonia circuit, copper or plastic tubing for glycol circuit
Efficiency Enhancement Features	None[1]
Additional Refrigerant Cycle Features	Reversing valve to reverse refrigerant flow for heat pumping, Refrigerant Charge Compensator, Suction Line Accumulator
Secondary Loop Features	Water- Propylene Glycol loop serving Hydronic Air-Handler, Propylene Glycol Pump, Expansion Tank with Diaphragm
Sources: 1) Hrnjak, P. et al, 2) Multi aqua	

[1]: No energy-efficiency enhancements beyond the inherent efficiency advantages of using ammonia

Brazed-Plate Heat Exchanger

The brazed-plate heat exchanger provides heat transfer between the outdoor primary loop (ammonia) and the indoor secondary loop (water- propylene glycol). This heat exchanger must be reinforced and protected to insure that the primary refrigerant does not enter the secondary loop.

A brazed-plate heat exchanger consists of several corrugated plates placed together and sealed. The two fluids flow through separate channels defined by the plates. In this heat exchanger, the plates are made of stainless steel and the brazes are made of nickel. The nickel brazes (unlike copper brazes) will not corrode when meeting ammonia.

The brazed heat exchanger is a commercial product from an ammonia chiller prototype developed by Hrnjak, P. et al. To validate this approach, research on the 5-ton light commercial heat pump chiller system showed it uses a brazed plate heat exchanger as well.

Table 4-6 shows some initial characteristics of this heat exchanger.

Table 4-6: Ammonia Brazed Heat Exchanger

Characteristic	Description
Type of Heat Exchanger	Nickel Brazed Plate Heat Exchanger
Materials	Plates and Connections: Stainless Steel Brazes: Nickel
Heat Exchanger Height	12.1 inches
Width	4.3 inches
Depth	2.8 inches
Weight	10.1 lbs

Source: Matrix Process Solutions: "Alfa Laval" brand
http://www.matrixps.com/products/alfalaval/heatex/PD_Leaflets/82_83_PHE_NB14_76_gb.pdf

Microchannel Outdoor Coil

Microchannel heat exchangers some advantages for ammonia systems, over round-tube configurations.

- Less refrigerant charge per capacity delivered
- Equivalent heat transfer performance in a more compact size

However, Padhmanabhan, Sankar et al. noted that microchannel heat exchangers experienced more frequent frosting and greater performance impacts in frosting conditions, due to imperfect defrosting performance. These heat exchangers may require further development to assure their viability for use in as outdoor heat exchangers for heat pumps. It may be necessary instead to use conventional round-tube heat exchangers in the ammonia system, in which case the heat exchanger size and system size may have to increase in order to achieve comparable efficiency levels. Such a change would also result in greater refrigerant charge.

The heat exchanger dimensions are based on an ammonia chiller prototype developed by Hrnjak, P. et al; the face area was proportionally adjusted based on the required capacity. Table 4-7 below contains preliminary specifications for the outdoor coil.

Table 4-7: Ammonia Outdoor Coil

Characteristic	Description
Type of Heat Exchanger	Microchannel
Cooling Medium	Air/Refrigerant
Materials	Aluminum
Capacity	Sized for a 3-ton heat pump unit
Channel Diameter	0.03 inches
Heat Exchanger Tubes	38 Tubes
Heat Exchanger Face Area	2.3 square feet
Heat Exchanger Depth	0.83 inches
Fins Per Inch	20
Fan Power	0.5 HP
Source: Hrnjak, P. et al	

Propylene Glycol Loop

The primary loop will contain a water- propylene glycol solution and flow between the occupied space and the outdoor chiller. Table 4-8 below contains preliminary specifications for the propylene glycol loop.

Table 4-8: Ammonia Propylene Glycol Loop

General Loop Characteristics	Description
Capacity	3-tons
% Glycol in Water Loop	0-50%[1]
Connective Piping Material	Copper
Pump Size	0.5 HP
Additional Features	Expansion Tank with Diaphragm
[1]: Dependent on the actual outdoor conditions experienced by the unit Source: Rittling Hydronics	

The propylene glycol loop includes an expansion tank to address propylene glycol thermal expansion. This is typical for modern water heating systems, such as the 5-ton light commercial heat pump chiller system illustrated above. UL requirements have not been developed for ammonia chiller/heaters used in residential applications. However, the possibility exists that the secondary loop piping will have to be able to withstand elevated pressure levels without resorting to pressure relief if the propylene glycol/refrigerant heat exchanger develops an internal leak that can transfer ammonia refrigerant into the propylene glycol loop.

A propylene glycol loop that is exposed to cold temperature conditions (during heat pump mode) may require additional preventive measures to assure reliable cold startup. Cold propylene glycol can have a very high viscosity, requiring measures such as a larger pump (Commercial Hydronics I) or heaters to assure glycol temperature remains sufficiently warm for startup.

Indoor Fan-Coil

The system will need an air-handler sized to 3 RT to deliver the air throughout the home. The fan coil dimensions are based on the specifications from a commercial hydronic fan-coil; the face area was proportionally adjusted based on the required capacity. Table 4-9 below contains preliminary specifications for the indoor- fan-coil. The fan-coil unit may also require a supplementary resistance heating coil.

Table 4-9: Ammonia Indoor Fan-Coil

Characteristic	Description
Type of Heat Exchanger	Tube and Fin
Materials	Copper Tubing with Aluminum Fins
Fan Coil Face Area	3.2 square feet
Fan Coil Tube Diameters	0.5 inch
Fan Coil Tube Rows	4 row coil
Fan Coil Fins Per Inch	12
Fan motor size	1/4 HP output
Source: Rittling Hydronics and Navigant estimates	

Semi-Hermetic Scroll Compressor
Compressor manufacturers have developed scroll compressors that are compatible with ammonia. These compressors use a semi-hermetic motor that contains aluminum windings (instead of copper), which makes it resistant to ammonia. The efficiency of these compressors is competitive with current HCFC-22 compressors, allowing ammonia air-conditioning systems to achieve similar efficiencies to current equipment (Oku, Tatsuya. et al).

Heat Pump Features
A reversing valve, a refrigerant charge compensator, and a suction line accumulator are included in the design to allow for heat pump operation of the cycle. The reversing valve allows for switching between cooling and heat pumping operation. The refrigerant charge compensator will balance the refrigerant charge differences for air-conditioning mode versus heat pump mode by storing refrigerant charge; the chiller configuration makes it easier to achieve a volume ratio of 1 to 1 between condenser and evaporator (eliminating the need for a charge compensator), but we provided one in our design to be conservative. Finally, the suction line accumulator will prevent liquid slugs from damaging the compressor, during cold start.

The secondary loop containing the water- propylene glycol solution can be heated or cooled by the primary loop; no changes are necessary for this part of the configuration.

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4.3 *Propane*

The sections below describe our configuration for propane. The selected configuration for propane is a 0.34 ton cooling and heating room air conditioner system. The target efficiency for a fully developed propane system would be the same as a conventional R-410A system. Our proposed system is intended to lay out a design path to reach this goal, but further research and development is required to finalize the design details of the system and establish the viability of the component selections. The room air conditioner has been designed to use 150 g of propane as a refrigerant. The system meets all of the code requirements listed in Section 2.3 above.

The single-packaged, portable configuration of a room air conditioner is the only configuration that meets the requirements of ASHRAE 15 and UL 484. To meet the charge requirements in the standards, the room air conditioner uses microchannel heat exchangers.

The sections below describe:

- The key design parameters used to design the system and size the components
- The physical positioning of all relevant components and sections
- The components that are used by this system

4.3.1 Key Design Parameters

Table 4-10 contains the key design parameters for the propane room air conditioner. These design parameters will guide the sizing of the key components and any relevant safety features. The capacity and charge were proportionally adjusted from a prototype designed by Hoehne, M.R. and Hrnjak, P.S., to meet a charge size of 150g.

Table 4-10: Design Parameters for Propane System

Design Parameters	Value
Cooling Capacity	0.34 RT
Target Efficiency	11.0 EER[1,2]
System-type	Room Air Conditioner
Applicable Standards	UL 484, ASHRAE 15
Refrigerant Charge	150g
Design Requirements	Charge Minimization, Ignition Prevention
Charge Minimization Techniques	Microchannel Indoor Coil, Microchannel Outdoor Coil
Ignition Prevention Techniques	Totally-enclosed air-over double-shafted motor, ignition-proof or enclosed electronics

[1]: Efficiency level from DOE RAC DFR. Compliance with these standards will be required on June 1, 2014.
[2]: Due to the low technical readiness of the design options discussed, further research and development may be required to assure that the target efficiencies are attained.

Because the standards limit the amount of charge that can be used in a room air conditioner, this is the largest system that can be used. Consequently, a 3-ton house would have to use 9 room air conditioners, while a 5-ton house would have to use 15 room air conditioners.

4.3.2 Layout

Figure 4-4 below shows a schematic of the full refrigeration system and the propane's relation to the occupied space. The low refrigerant charge allows the refrigeration system to be placed in direct contact with the outdoor space.

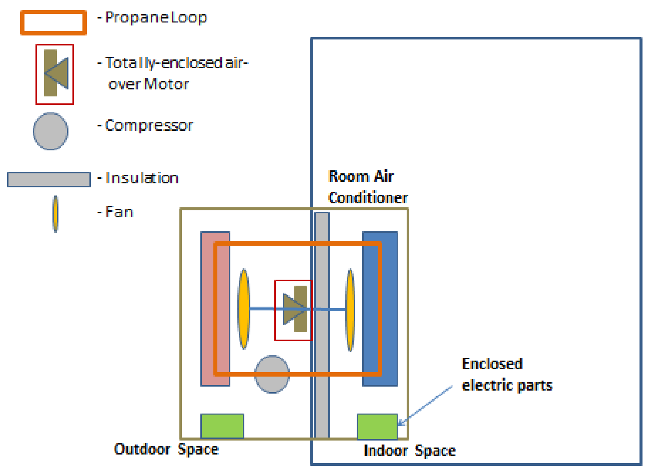

Figure 4-4: Layout of the Full Propane System

4.3.3 Key Components

Table 4-11 below contains a list of key system components. Detailed descriptions of the heat exchangers, compressor, and safety features follow the table.

Table 4-11: Key Components for Propane System

Components	Refrigerant System Specific Features
Heat Exchangers	Microchannel Evaporator, Microchannel Condenser
Compressor	R-290 Rotary Compressor
Expansion Device	2 Capillary Tubes
Unique Safety Features	• All electrical components should be ignition-proof, separated from the main chamber, or be located in an enclosure • Totally-enclosed air-over double-shafted motor
Additional Refrigerant Cycle Features	Reversing valve to reverse refrigerant flow for heat pumping

The following sections contain detailed descriptions of some of the key design components.

Microchannel Heat Exchangers
Microchannel heat exchangers some advantages for propane systems, over round-tube configurations.

- Less refrigerant charge per capacity delivered
- Equivalent heat transfer performance in a more compact size

However, Padhmanabhan, Sankar et al. noted that microchannel heat exchangers experienced more frequent frosting and greater performance impacts in frosting conditions, due to imperfect defrosting performance. These heat exchangers may require further development to assure their viability for use in as outdoor heat exchangers for heat pumps. However, use of microchannel heat exchangers for both the evaporator and the condenser reduce refrigerant charge, and are essential to allow the room air conditioner to achieve the target capacity given the charge limitations imposed by applicable safety codes. It may be necessary to limit this design to air-conditioning only.

The brazed heat exchanger dimensions in Table 4-12 are from a propane prototype developed by Hoehne, M.R. and Hrnjak, P.S.; the face area was proportionally adjusted based on the actual capacity of our system.

Table 4-12: Design Parameters for Propane System

Characteristic	Outdoor Coil	Indoor Coil
Type of Heat Exchanger	Microchannel	Microchannel
Material	Aluminum	Aluminum
Cooling Medium	Air/Refrigerant	Air/Refrigerant
Capacity	Sized appropriately for a 0.38 RT room air conditioner	
Channel Diameter	0.14 inches	0.14 inches
Heat Exchanger Tube Pitch	0.38 inches	0.45 inches
Heat Exchanger Face Area	0.87 sq. feet	0.51 sq. feet
Heat Exchanger Depth	0.7 inches	1.0 inches
Fins Per Inch	16.7	16.7
Fan Motor Size	1/25 HP Double-shafted motor	
Source: Hoehne, M.R. and Hrnjak, P.S.		

Compressor
Compressor manufacturers have developed rotary R-290 compressors whose efficiency is comparable to current R-410A systems (Hasse, Dr. Volkmar). Gree Electric is using these compressors to achieve EERs of close to 12 in mini-split systems. The compressors incorporate an improved electric connection to reduce the risk of ignition and require material changes to make them more compatible with propane applications.

Motor and Electrical Components
To prevent possible ignition, the design includes sealed fan motors and a separate enclosure for all electric boards, switching components, and capacitors. This includes:

- A totally-enclosed air-over (TEAO) motor should be used for the 1/25 HP fan motor, which will allow it to meet the requirements of IEC standard 60079-15:2010 (as referenced by UL Standard 484).
- The remaining electrical parts (capacitors, circuit boards, switches) should be sealed off from the main refrigeration circuit, so they do not come into contact with any potential leaks. A hermetic enclosure encloses these parts.

Heat Pump Features
A reversing valve and is included in the design to allow for heat pump operation of the cycle. The reversing valve allows for the high-side and low-sides of the cycle to switch places.

4.3.4 Sources

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4.4 HFO-1234yf

The sections below describe our configuration for HFO-1234yf. Our selected configuration for HFO-1234yf is a 3-ton split-system air-conditioner and heat pump. The target efficiency for a fully developed HFO-1234yf system would be the same as a conventional R-410A system. Our proposed system is intended to lay out a design path to reach this goal.

The system meets all of the code requirements listed in Section 2.3 of this report. In ASHRAE Standard 15, the HFO-1234yf split-system is limited to 6.6 lbs of refrigerant. Figure 4-5 below shows the charge sizes for typical R-410A equipment using round-tube heat exchangers (Ingram's Water and Air Equipment). Current equipment using R-410A would be challenged to meet this limit. Assuming a 20% charge increase for HFO-1234yf, similar equipment using HFO-1234yf would not meet this limit.

Based on work by Hoehne, M.R. and Hrnjak, P.S., microchannel heat exchangers have the potential to lower the system charge by 40% when used for both the indoor and outdoor coils. Applying this conversion to the assumed HFO-1234yf charge sizes, HFO-1234yf equipment using microchannel heat exchangers can meet the 6.6 lbs limit in ASHRAE Standard 15 (up to 42,000 Btu/h). A focused development effort may lead to the potential for higher capacity within the charge limit, but this is not certain based on the available research described in the open literature. The figure below shows the relationship between actual and projected charge levels, and the ASHRAE Standard 16 limit.

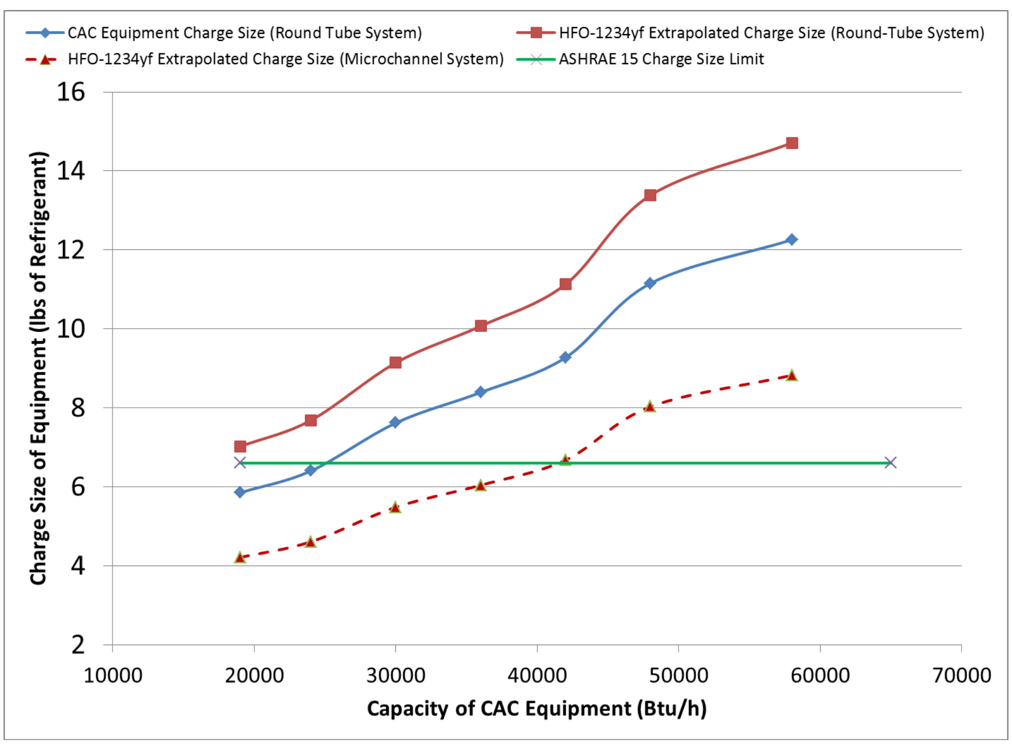

Figure 4-5: Comparison of Equipment Charge Sizes to ASHRAE 15 Limits

Source: Ingram's Water and Air Equipment

Based on this analysis, the HFO-1234yf configuration will use microchannel heat exchangers to meet the charge limits found in ASHRAE 15. The configuration will be able to hit the target 3.0 RT capacity, but will be unable to extend to the desired 5.0 RT.

Studies by Leck showed that an R-410A system, using HFO-1234yf as a drop-in refrigerant, may be 14% less efficient than R-410A equipment for cooling, and 12% less efficient than R-410A equipment for heating. However, studies by Fujitaka, Akira et al. indicate that the COP of HFO-1234yf cycles is comparable to R-410A cycles (though at much reduced capacity). This indicates that additional efficiency measures and optimization of HFO-1234yf heat exchangers (to account for pressure drops) is needed to ensure similar efficiency performance. In addition, further research and development are needed to ensure the performance of other immature HFO-1234yf components.

The sections below describe:

- The key design parameters used to design the system and size the components
- The physical positioning of all relevant components and sections
- The components that are used by this system

4.4.1 Key Design Parameters

Table 4-13 contains the key design parameters for the HFO-1234yf air-conditioning system. These design parameters will guide the sizing of the key components and any relevant safety features.

Table 4-13: Design Parameters for HFO-1234yf System

Design Parameters	Value
Capacity	3 RT
Target Efficiency	13 SEER; 7.7 HSPF[1]
System-type	Direct split-system with indoor and outdoor units
Applicable Standards	ASHRAE 15, UL 1995
Refrigerant Charge	6.0 lbs
Design Requirements	Charge minimization
Charge Minimization Techniques	Microchannel outdoor coil, microchannel indoor coil
[1]: Due to the low technical readiness of the design options discussed, further research and development may be required to assure that the target efficiencies are attained.	

The details in this section are specifically designed for a 3-ton air-conditioning system. Based on our calculations, a single system using the maximum of 6.6 lbs of refrigerant would have a capacity of 3.5 RT. Larger systems would need to employ multiple circuits to meet the code requirements.

4.4.2 Layout

Figure 4-6 below shows a schematic of the full refrigeration system and the HFO-1234yf's relation to the occupied space. The low charge and low flammability of the refrigeration system allows the refrigeration system to be placed in direct contact with the indoor space.

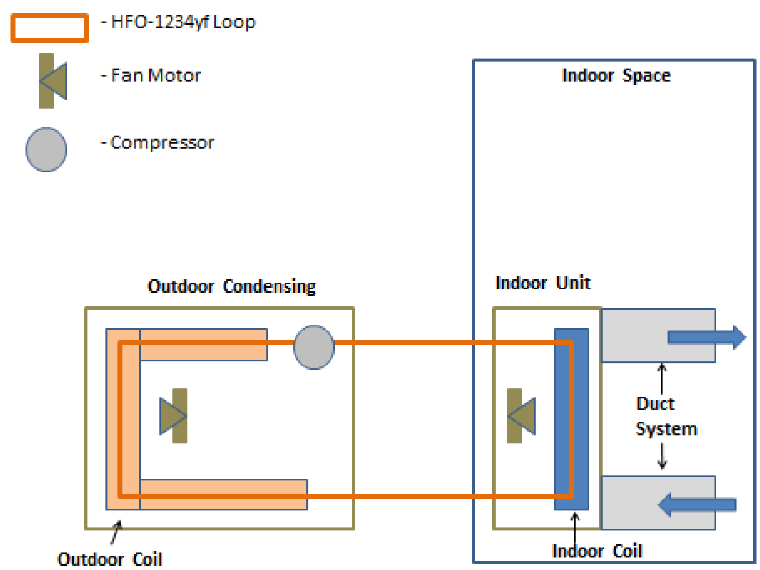

Figure 4-6: Layout of the Full HFO-1234yf System

4.4.3 Key Components

Table 4-14 contains a list of key system components. Detailed descriptions of the heat exchangers, compressor, and safety features follow the table.

Table 4-14: Key Components for HFO-1234yf System

Components	Refrigerant System Specific Features
Heat Exchangers	Microchannel Evaporator, Microchannel Condenser
Compressor	Scroll or Rotary compressor
Expansion Device	2 Thermostatic expansion valves
Efficiency Enhancement Features	Suction-Line Heat Exchanger
Additional Refrigerant Cycle Features	Reversing valve to reverse refrigerant flow for heat pumping, Block valve connectors to connect tubing sections from the indoor and outdoor units, Refrigerant Charge Compensator, Suction Line Accumulator

The following sections contain detailed descriptions of some of the key design components.

<u>Scroll or Rotary Compressor</u>
Several compressor types have been tested and modeled in HFO-1234yf stationary A/C systems. However, there are no commercially-available specifications for HFO-1234yf compressors for stationary A/C systems. Both scroll and rotary compressors may be suitable options; Okazaki, Takashi et al. performed drop-in tests in a 4.0 kW room air conditioner using a rotary compressor, and both scroll and

rotary compressors have been tested in mobile air-conditioning applications (Ikegami, Tohru et al). At the time of publication, we were not aware of any commercially-available compressors for stationary air-conditioning applications (either as scrolls or rotaries).

At this time, it is premature to suggest a preference for a scroll or rotary compressor at this time, due to the limited available performance data.

<u>Microchannel Heat Exchangers</u>
Microchannel heat exchangers some advantages for HFO-1234yf systems, over round-tube configurations.

- Less refrigerant charge per capacity delivered
- Equivalent heat transfer performance in a more compact size

However, Padhmanabhan, Sankar et al. noted that microchannel heat exchangers experienced more frequent frosting and greater performance impacts in frosting conditions, due to imperfect defrosting performance. These heat exchangers may require further development to assure their viability for use in as outdoor heat exchangers for heat pumps. However, use of microchannel heat exchangers for both the evaporator and the condenser reduce refrigerant charge, and are essential to allow the air conditioner to achieve the target capacity given the charge limitations imposed by applicable safety codes. It may be necessary to limit this design to air-conditioning only.

Table 4-15 below contains specifications for the two heat exchangers in this system. A few calculations were performed, including:

- The heat exchanger face areas were assumed to be equivalent to those in a typical R-410A split-system (DOE CAC TSD). Heat exchanger size reductions due to use of microchannel coils will offset the need for larger heat exchangers to meet efficiency and capacity targets.
- The heat exchanger depth, tube diameter, and fins per inch were taken from a microchannel study using R-134A (Nelson, S.M. and Hrnjak, P.S.).
- The fan motor sizes were assumed to be equivalent to those in a typical R-410A split-system (DOE CAC TSD). Because of the reduced pressure drop associated with the microchannel heat exchangers, these could be reduced by 5-10%.

Table 4-15: HFO-1234yf System Heat Exchangers

Characteristic	Outdoor Coil	Indoor Coil
Type of Heat Exchanger	Microchannel	Microchannel
Material	Aluminum	Aluminum
Cooling Medium	Air/Refrigerant	Air/Refrigerant
Capacity	Sized for a 3-ton heat pump unit	
Channel Diameter	0.05 inches	0.02 inches
Heat Exchanger Tube Pitch	0.4 inches	0.4 inches

Heat Exchanger Face Area	3024 sq. inches[1]	1152 sq. inches[1]
Heat Exchanger Depth	0.8 inches	0.8 inches
Fins Per Inch	21	17
Fan Motor Size	0.25 HP	0.45 HP
Source: Hoehne, M.R. and Hrnjak, P.S.		
[1]: The face area was assumed to be equivalent to a typical R-410A system, as described in the DOE CAC TSD.		

Block valve

According to ASHRAE 15, a direct HFO-1234yf system must use block valves (also known as connector or quick-connect valves) to connect the indoor and outdoor units (these connections would otherwise would require field brazing, which is prohibited). These valves must be paired and placed at the end of the refrigerant tubing, allowing for the indoor and outdoor units to be joined quickly and easily. The quick-connector valves should be sized to fit slightly larger suction lines (about 1" OD) and slightly larger liquid lines (a 0.75" OD).

Suction-Line Heat Exchanger

Current studies have shown that an HFO-1234yf air-conditioning system may be significantly less efficient than a comparable R-410A system without considering performance enhancement. According to tests on mini-split units in Leck and Yamaguchi 2, these systems will suffer an efficiency drop of at least 12%-14% in cooling and heating COP. To mitigate the potential efficiency loss compared to a conventional system, our proposed HFO-1234yf system uses a suction-line heat exchanger. More careful design study and testing will have to be conducted to determine whether additional efficiency improvement would be necessary in order to achieve parity with the efficiency levels of conventional heat pump systems.

The suction-line heat exchanger is a commercial product and used by Hoehne, M.R. and Hrnjak, P.S. The dimensions are described below in Table 4-16 below.

Table 4-16: Suction Line Heat Exchanger for HFO-1234yf System

Characteristic	Description
Type of Heat Exchanger	Concentric Heat Exchanger
Materials	Aluminum
Heat Exchanger Length	7.0 inches
Heat Exchanger Outer Diameter	1.3 inches
Heat Exchanger Weight	0.66 lbs
Source: Hoehne, M.R. and Hrnjak, P.S	

Heat Pump Features

A reversing valve, a refrigerant charge compensator, and a suction line accumulator are included in the design to allow for heat pump operation of the cycle. The reversing valve allows for the high-side and low-sides of the cycle to switch places, while the refrigerant charge compensator will balance the refrigerant charge differences for air-conditioning mode versus heat pump mode by storing refrigerant charge. The suction line accumulator will prevent liquid slugs from damaging the compressor, during cold start.

4.4.4 Sources

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5. Summary

This report presents system configurations for four candidate refrigerants in a residential air-conditioning system: carbon dioxide, ammonia, propane, and HFO-1234yf. Each configuration meets the safety requirements found in today's codes and standards, most notably ASHRAE Standard 15 and UL Standards 484 and 1995. Based on the safety requirements and pre-defined performance goals, each refrigerant adopted either a direct or indirect configuration. Further study of research designs and prototype configurations led to key design details of the most promising system configurations for the candidate refrigerants.

Each refrigerant poses unique challenges that will require additional design features to address. Table 5-1 shows the additional design features that were included in each of the systems designs. Due to the low technical readiness of many of the design options that are shown, further research and development is needed to finalize the actual design for each refrigerant.

Table 5-1: Recommended Additions to Baseline Design for Each Refrigerant

Refrigerant	Configuration	Additional Design Features
Carbon Dioxide	Direct split-system	• Microchannel Evaporator and Condenser • Hermetic scroll expander/generator for work-recovery with power electronics and controls for conversion to 60Hz power while maintaining optimized high-side pressure • More complicated valve system to reverse refrigerant flow for heat pumping
Ammonia	Indirect	• Brazed-Plate Evaporator and Hydronic Indoor Coil to replace single Refrigerant/Air Indoor Coil • Microchannel Condenser • Steel Tubing for Ammonia circuit, copper or plastic tubing for glycol circuit • Water-Propylene Glycol loop serving Hydronic Air-Handler, Propylene Glycol Pump, Expansion Tank with Diaphragm
Propane	Direct room air conditioner	• System has a capacity of 0.34 RT; several air conditioners will be needed to meet full cooling and heating needs • Microchannel Evaporator and Condenser • All electrical components ignition-proof, separated from the main chamber, or located in an enclosure • Totally-enclosed air-over double-shafted motor

HFO-1234yf	Direct split-system	• System can reach a maximum capacity of 3.5RT; larger systems will require multiple circuits • Microchannel Evaporator and Condenser • Suction-Line Heat Exchanger • Block Valve Connectors

The information found in this report can be used in subsequent study to provide additional definition of the system and component design details to support development of cost estimates for the systems.