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A2L REFRIGERANTS AND FIREFIGHTER TACTICAL CONSIDERATIONS

Final Report

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Executive Summary

The phase-down and restriction of the most common and widely used refrigerants was initiated in the late 1980's and has spurred innovation, both for the alternative refrigerants that have been introduced as well as in the equipment that uses them. Safety Group A2L refrigerants (lower toxicity and lower flammability) represent the most recent in the focus of deployable reduced GWP/zero ODP refrigerants. Studies conducted by the industry have shown that in order to reach the goals of the Kigali Amendment for global warming impact reduction it is likely that A2L refrigerants will be required. The fire service requested that data be developed to identify hazards to the fire service personnel when responding to fire events in occupancies with the new refrigerants. Specifically, they have identified the following areas where performance data of A2L refrigerants would assist them in their tactical considerations.

- a) Comparison and contribution of A1 and A2L refrigerants in a fire relative to heat and gases generated;
- b) Potential for flash fire, deflagration, or explosion hazards in residential and commercial applications; and
- c) Influence on fire dynamics from refrigerant leakage during fire service suppression and overhaul activities.

The data from the testing will be used by UL Fire Safety Research Institute (FSRI) to develop training materials for the fire service towards their tactical considerations. This activity is to be performed in a separately funded and contracted project following completion of this statement of work.

The following objectives for this investigation were identified in collaboration with AHRI and the fire service organizations:

1. Demonstrate through fire scenario tests the hazards that may be encountered by the fire service when fire involves Safety Group A2L refrigerants as compared to existing Safety Group A1 refrigerants; and
2. Prepare information for the later development of educational materials for the fire service for their tactical considerations.

The original plan called for testing two safety group A1 refrigerants (R-410A and R-466A) and two safety group A2L refrigerants (R-32 and R-454B). It was found in Scenario 1 that the facility's smoke abatement system was not able to scrub iodine from the exhaust gases. Use of R-466A was suspended because of this issue.

Based upon these objectives fire scenarios were designed as follows:

Scenario 1: Comparison and contribution of A1 and A2L refrigerants relative to heat and gases generated in an open flame.

Scenario 2: Hazards during suppression activity from change in fire dynamics in the hallway where firefighters may be advancing towards the fire room with a forced refrigerant release in ventilation-controlled conditions.

Scenario 3: This scenario was planned as optional pending a review of Scenario 2. The difference between Scenario 2 and Scenario 3 is that the leak would not be forced as in Scenario 2.

Scenario 4: Hazards in fire room during overhaul activity if firefighters action results in a refrigerant line break.

Scenario 5: Fire conditions in a below grade closed room without any air movement, having an excessive amount of refrigerant pooling, well above the allowable limits of refrigerant to demonstrate how refrigerant burns when ignited with a flame.

(This scenario was added to the original plan based upon input from UL FSRI and fire service.)

The results for each scenario relevant for firefighter tactical considerations are summarized here.

Summary of Findings for Considerations by Firefighters

The following provides a summary of findings for consideration by firefighters relative to the objectives of this investigation.

Figure Es-1 may be used to provide comparison of numerical data in the report to common examples.



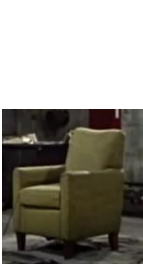
Candle (80 W)



Plastic waste basket with small wax cups (50 kW)



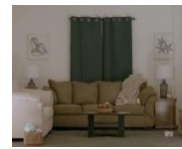
30-gallon trash container with construction debris (150-300 kW)



Upholstered furniture (2000 kW)



Overstuffed Sofa (4000 kW)



Living room with adequate ventilation (7000 kW)

Figure Es-1 – Examples for comparison of Heat Release Rate Data

Table Es-1 may be used to develop inferences on the hazards relative to heat flux exposure from fires.

Table Es-1 – Hazard from Heat Flux Exposure in Fires

Heat Flux (kW/m ²)	Comparison
< 1	Thermal radiant heat from the sun (cloudless sky)
3 to 5	Heat flux that will cause pain to human skin within seconds
20	Heat flux at the floor (8 ft ceiling height) during flame rollover/beginning of flashover
84	Heat flux exposure during Thermal Protective Performance (TPP) test for Firefighter Turnout Gear
60 to 200	Range of heat flux during flame impingement on a surface

Comparison of A1 and A2L refrigerants exposed to an open flame.

This investigation (Scenario 1) showed that a leak with diameter a 1.2 mm (0.047 in.) hole released the refrigerant as a jet. This resulted in the jet pushing the flames towards the wall increasing the temperature and heat flux exposure on the wall. The temperature increase for both A1 and A2L refrigerants was approximately 200°C. The heat flux exposure on the wall for both A1 and A2L refrigerants increased by approximately 20 kW/m².

There was no flash fire or deflagration observed when the refrigerant jet interacted with the existing flame. The heat release rate of the flame with the jet increased by approximately 140 kW from the combustion of refrigerant in the flame. However, there was no visible increase in flame height with either A1 or A2L refrigerants.

Both A1 and A2L refrigerants generated hydrogen fluoride (HF) gas in quantities considered hazardous without personal protective equipment (PPE). There was not a significant relative difference in HF gas generation between R410A (A1) and other lower GWP refrigerants (A1, A2L) used in this investigation.

Gaseous hydrogen iodide (HI) was not detected in the open path FTIR instrument. Some concentrations of HI were measured using the bubbler method during R-466A releases.

Tactical Considerations for Firefighters Advancing to Room of Fire Origin

This investigation (Scenario 2) examined conditions at a hallway entrance where firefighters were preparing to advance their attack on the room of origin. The fire was ventilation limited, resulting in hot gas layer temperatures in excess of 600°C (1100°F). The temperatures in the hallway, below 32 in.

height, were less than 100°C. The refrigerant release (either A1 or A2L) did not increase temperatures at the hallway entrance.

Temperatures at the HVAC unit were high enough to cause brazed joints to fail which would have led to a catastrophic release of refrigerant in the room of fire origin.

For both A1 and A2L refrigerants, heat flux exposure at the hallway entrance was less than 5 kW/m² at the 3-foot level. This heat flux level is sufficient to cause pain to exposed skin within seconds.

The ventilation limited fire developed heat release rates of about 2300 kW. When the refrigerant was released into this fire there was no observation of a deflagration or a flashing of additional flames and smoke into the hallway.

Hydrogen fluoride (HF) was detected in the hallway for both A1 (R-410A) and A2L (R-32) refrigerants. The levels of HF generated were comparable. R-466A was not tested in this scenario so hydrogen iodide (HI) was not measured.

Since there was not an increased hazard from Scenario 2 with forced release of refrigerant, Scenario 3 was not conducted.

Tactical Considerations for Firefighters' Overhaul Activities in Room of Fire Origin

Fast refrigerant Leak (Scenario 4)

This scenario investigated conditions developed if a charged refrigerant line were to break during overhaul activities. The fast leak resulted in a jet of refrigerant that quickly mixed with air. This led to small increases in the fire size as it flowed through a pre-existing fire in the room. The increased fire size was about the same as a small plastic trash can fire (50 to 100 kW). Visual observations showed the jet pushed the flames to the side. The heat flux from the pushed flame was less than 1 kW/m². This value is about the same as the thermal radiant heat from the sun on a clear day. These results were comparable for both A1 and A2L refrigerants. HF was generated in quantities hazardous without PPE. The relative difference between A1 and A2L refrigerants were within 2%.

Pooled Refrigerant Ignition (Scenario 5)

This investigation examined the effect of igniting a large quantity of refrigerant pooled at the floor level from a slow leak of refrigerant (heavier than air) with very little mixing with the air in the room. This scenario simulated a leak occurred in a basement utility room of a large residence that required a 5-ton ducted AC unit and the associated charge needed to operate. For the pool of A1 refrigerant (R-410A) some flaming was observed at the igniters but did not lead to spread of flame in the room.

The pool of A2L refrigerant (R-32) was ignited by the fire source and spread away from the ignition source to other ignitable concentrations in the room. The resulting fire grew slowly over a period of 40 seconds. There was no observation of a fast fireball or deflagration in the room. At one minute after ignition, camera views in the room were obstructed by the smoke. The heat flux at 3 feet distance from the ignition peaked at 15 kW/m² which can cause 2nd degree burns to exposed skin in about 7 seconds.

Temperatures above the ignition point climbed to between 300°C and 400°C (570°F to 750°F). Flames were observed to flow out of the room's doorway.

Levels of HF gas, hazardous without PPE, were generated for both A1 and A2L refrigerants. The levels of HF from the A1 refrigerant were observed to be generated near the ignition source and developed at a much slower pace than the A2L refrigerant. The levels of HF from the A2L refrigerant were significantly higher and faster developing due to spread of the fire to the pooled layer in the room.

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1. Background

The phase-down and restriction of the most common and widely used refrigerants was initiated in the late 1980's and has spurred innovation, both for the alternative refrigerants that have been introduced as well as in the equipment that uses them. Safety Group A2L refrigerants (lower toxicity and lower flammability) represent the most recent in the focus of deployable reduced GWP/zero ODP refrigerants. Studies conducted by the industry have shown that in order to reach the goals of the Kigali agreement for Global Warming impact reduction it is likely that A2L refrigerants will be required. The fire service requested that data be developed to identify hazards to the fire service personnel when responding to fire events in occupancies with the new refrigerants. Specifically, they have identified the following areas where performance data of A2L refrigerants would assist them in their tactical considerations.

- a) Comparison and contribution of A1 and A2L refrigerants in a fire relative to heat and gases generated;
- b) Potential for flash fire, deflagration, or explosion hazards in residential and commercial applications; and
- c) Influence on fire dynamics from refrigerant leakage during fire service suppression and overhaul activities.

The data from the testing will be used by UL Fire Safety Research Institute (FSRI) to develop training materials for the fire service towards their tactical considerations. This activity is to be performed in a separately funded and contracted project following completion of this statement of work.

2. Objectives

The objectives of this work were as follows:

1. Demonstrate through fire scenario tests the hazards that may be encountered by the fire service when fire involves Safety Group A2L low flammability refrigerants as compared to existing Safety Group A1 and new Group A1 refrigerants; and
2. Prepare information for the later development of educational materials for the fire service for their tactical considerations.

3. Scope

The original scope of this project included scenarios 1 through 4 (outlined below). Review of the data resulted in revision to the original plan to meet the concerns of the fire service. These modifications were made in collaboration with the AHRTI project monitoring subcommittee (PMS), UL FSRI and fire service representatives.

Scenarios were performed with one or two A1 refrigerants and one or two A2L refrigerants selected by the AHRTI 8028 PMS. Each fire scenario included a baseline without the presence of a refrigerant to measure the relative contribution of a refrigerant involved in the same scenario.

The five scenarios performed in this project are as follows:

1. Scenario 1: Comparison and contribution of A1 and A2L refrigerants relative to heat and gases generated in an open flame.
2. Scenario 2: Hazards during suppression activity from change in fire dynamics in the hallway where firefighters may be advancing towards the fire room with a forced refrigerant release in ventilation-controlled conditions. The scenario was modified by including both a forced leak external to the air-conditioning unit and a forced leak within the air-conditioning unit.
3. Scenario 3 (Optional): Similar to Scenario 2 with refrigerant release due to system failure in the fire. (Not conducted since Scenario 2 met the objectives for the fire service.) See section 9.3 Scenario 3 for a full explanation.
4. Scenario 4: Hazards in fire room during overhaul activity if firefighters action results in a refrigerant line break.
5. Scenario 5 (Added): Fire conditions in a below grade closed room without any air movement, having an excessive amount of refrigerant pooling, well above the allowable limits of refrigerant to demonstrate how refrigerant burns when ignited with a flame.

4. Technical Plan

The technical plan for this project consisted of the following tasks:

- Task 1 – Plan, construct, and acquire equipment, refrigerants, and refrigerant release method
- Task 2 – Conduct tests
- Task 3 – Develop a Technical Report (this report)

The results from the technical plan are presented in the following sections.

5. Refrigerants

One Safety Group A1 and two A2L refrigerants were selected by AHRI. All refrigerants used the project were provided by an AHRI member. A summary of relevant refrigerant characteristics is shown in Table 1.

Table 1 – Refrigerant Properties

Refrigerant Characteristic	R-410A	R-32	R-454B	R-466A
Safety Group [1]	A1	A2L	A2L	A1
Chemicals by weight %	R-32, R-125 (50, 50)	R-32 (100)	R-32, R-1234yf (68.9, 31.1)	R-32, R-125, R-13I1 (49, 11.5, 39.5)
Compounds	CH ₂ F ₂ C ₂ HF ₅	CH ₂ F ₂	CH ₂ F ₂ C ₃ H ₂ F ₄	CH ₂ F ₂ C ₂ HF ₅ CF ₃ I
RCL (ppm v/v) [1]	140,000	36,000	19,000	30,000 [2]
LFL (kg/m ³) at 23°C, 101.3 kPa, 50% rh [3]	NA	0.306	0.297 (WCF)	NA
ODP*	0	0	0	~0
GWP ₁₀₀ **	2088	675	466	733
Burning Velocity (cm/s) at 23°C, 101.3 kPa, <1% rh	0	6.7	5.2	0
Minimum Ignition Energy (mJ)	NA	30-100 (Es=200)	100-300 (Es***=200)	NA
Heat of Combustion (MJ/kg) at 25°C, 101.3 kPa, 0% rh	5.91	9.5	9.9	5.45

*ODP – Ozone Depletion Potential

**GWP – Global Warming Potential, 100-year integration time horizon [4].

*** -- Statistical MIE (Es) is an estimation technique to estimate the actual ignition energy to a more precise amount of detail, the tolerance is on the order of +/- 50%.

6. A/C Equipment

The air handlers used in Scenario 2 were provided by an AHRI equipment manufacturer. The installation is shown in Figure 1. The air-conditioning equipment is a typical indoor unit for a large (5-ton) residential sized split system, including an ‘A-coil’ evaporator and fan.



Figure 1 – Air handler used in Scenario 2

7. Test Facility and Hazard Controls

Testing was conducted in UL’s Northbrook large-scale test facility with a test room 42×47×43 ft. high. The test room is outfitted with a 14 by 14-foot square exhaust hood attached to the building’s smoke abatement system. Figure 2 shows the exhaust hood during a calibration fire. All the tests in this investigation were located under this exhaust hood.



Figure 2 – ADD room Calorimeter hood with a calibration fire in progress

7.1. Test Setups

The test program required two test setups. The test setup for Scenario 1 is shown in Figure 3. The three-sided room was constructed entirely within the footprint of the hood. This enabled the released combustion products to be collected and processed by the smoke abatement facility,



Figure 3 – Scenario 1 Test Setup

Scenarios 2, 4, and 5 were performed in a building constructed under the hood as shown in Figure 4. In these scenarios, the hallway exit was located under the center of the hood allowing the products of combustion to be captured and processed by UL's smoke abatement system. The doors on either side of the hallway exit were closed during testing.

No special room temperature and humidity control was used and the conditions were typical for conditions inside the laboratory in November and December.



Figure 4 – Test Setup for Scenarios 2, 4, and 5

7.2. Hazard Controls

The conduct of this test program involved hazards to test personnel, test facilities and the environment. Potential hazards to personnel and the test facility included non-flammable and flammable gases, fire, suffocation, toxic gases, electric shock, frostbite, and mechanical hazards. Hazards were addressed by:

- Elimination.
- Engineering controls.
- Administrative controls.
- Personal protective equipment.

7.2.1. Hazard Elimination

Potential hazards in the workspace were assessed as they were introduced into the laboratory workspace. When possible, hazards were eliminated from the workspace entirely. For example, unused or no longer to be used compressed gas cylinders were removed from the facility and stored in a nearby tank storage facility. Hazards that could not be eliminated immediately were periodically reassessed to determine if changes in the test program enabled the hazards to be eliminated. Hazards that could not be eliminated were addressed through engineering controls, administrative controls or personal protective equipment.

7.2.2. Engineering Controls

When any A1 or A2L fluorinated refrigerant ($C_xH_yF_z$) is combusted, it produces heat, water (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen fluoride (HF), and other products resulting from incomplete combustion. The test facility was constructed such that heat, and gases were exhausted from the test room by the collection hood and processed by UL's smoke abatement system without the risk of personnel exposure.

Wall-mounted open sprinkler heads were in each room to initiate suppression activities. The hallway was outfitted with an open ceiling sprinkler head. Sprinklers were connected to a remote activation switch in the control room.

All necessary actions required to initiate the tests and provide input to tests were engineered to be remotely controlled by personnel located outside of the test room.

7.2.3. Administrative Controls

Standard operating procedures (SOPs) were developed in order to provide laboratory staff with guidance for safe test setup and conduct. SOPs consisted of assigning pre-test, test and post-test roles to every member of the project team. Pre-test safety actions were monitored via a checklist reviewed by the lead technical engineer.

Prior to initiating a test, all staff evacuated the test room. Actions needed to initiate and administer a test were conducted remotely from the control room.

Before any staff was permitted entry into the test room, the test facility was exhausted through the collection hood. Additionally, hydrogen fluoride (HF) concentration sensors within the test facility were monitored for HF and combustion products. Oxygen, carbon dioxide, and carbon monoxide levels were also monitored.

Electrical equipment requiring hands-on work was de-energized within the circuit breaker for the given equipment; the equipment was switched off, and unplugged. All electrical cabling was verified de-energized with a digital multi-meter.

Hazards typically associated with handling refrigerants by tradesmen were handled only by staff with appropriate training and authorization.

7.2.4. Personal Protective Equipment

UL's standing safety requirement for personnel entering the test facility includes hard hat, safety shoes, and safety glasses.

Additional protective equipment included:

- Long sleeve shirts and long pants.
- Refrigerant operations were conducted by UL trained personnel.

7.3. Refrigerant Discharge Control System

The mass discharge rates in this investigation had initial flow rates of 50 g/s (Scenarios 1, 2, 4) and 30 g/s (Scenario 5). These are considered catastrophic leak rates that seldom occur and only occur when there is a major break in a refrigerant line. The system consisted of a 50 lb. recovery tank that was evacuated and filled with the amount of refrigerant to be discharged. Two modes of discharge were created. The first was called a constant pressure method, where liquid refrigerant was discharged through a nozzle throughout the entire discharge. The recovery tank was filled such that the entire discharge remained in the liquid state up to the discharge orifice.

The second method was called a pressure decay method which is more representative of a catastrophic leak in an HVAC unit. In this case, refrigerant tank was filled with a mass of refrigerant between 15 and 20 lbs. based on charge that would be in a 5-ton split units with 100 ft of interconnecting lines. Note the charge was adjusted to account for the different charge levels for the selected refrigerant. A refrigerant discharge was conducted using the liquid valve on the tank. Since all the refrigerant mass was intended to be discharged, there was a point during the discharge that tank pressure dropped below saturation pressure. This resulted in a two-phase flow in the discharge lines. While the initial discharge rate met the target of either 50 or 30 g/s, the final discharge rate was typically less than 5 g/s. Note that the refrigerants boil at -57.0 to -60.9 °F so any liquid quickly flashes to vapor. In addition, the speed of sound is low so there can be a supersonic shock wave in the refrigerant release device.

Figure 5 compares the two methods of release. The constant pressure release method was not entirely at constant pressure due to draining liquid from the tank. The pressure decay method on the right shows and initial flow rate near 50 g/s followed by a period of two-phase flow. The final flow rate was less than 5 g/s.

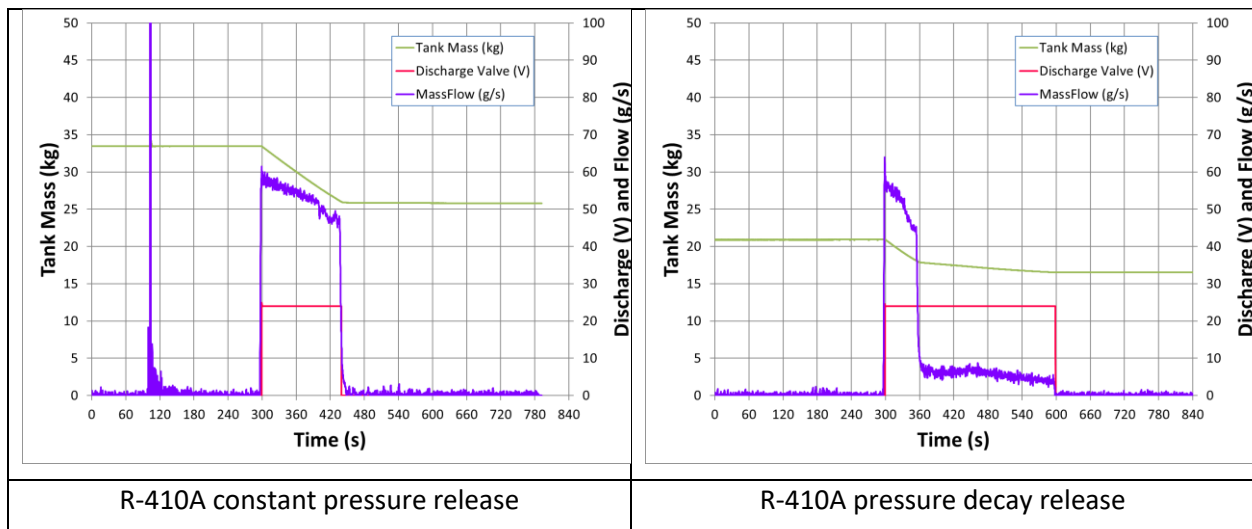


Figure 5 – Constant pressure compared to pressure decay discharge

Figure 6 compares the recorded tank and system pressure seen in both release methods. The pressure spikes seen in the pressure decay method are due to flashing at the locations of the pressure transducers. The pressure transducers had a maximum range of 500 psig which explains the chopped



shape of the system pressure curve in the right-hand chart. These pressures curves were typical of all four refrigerant discharges.

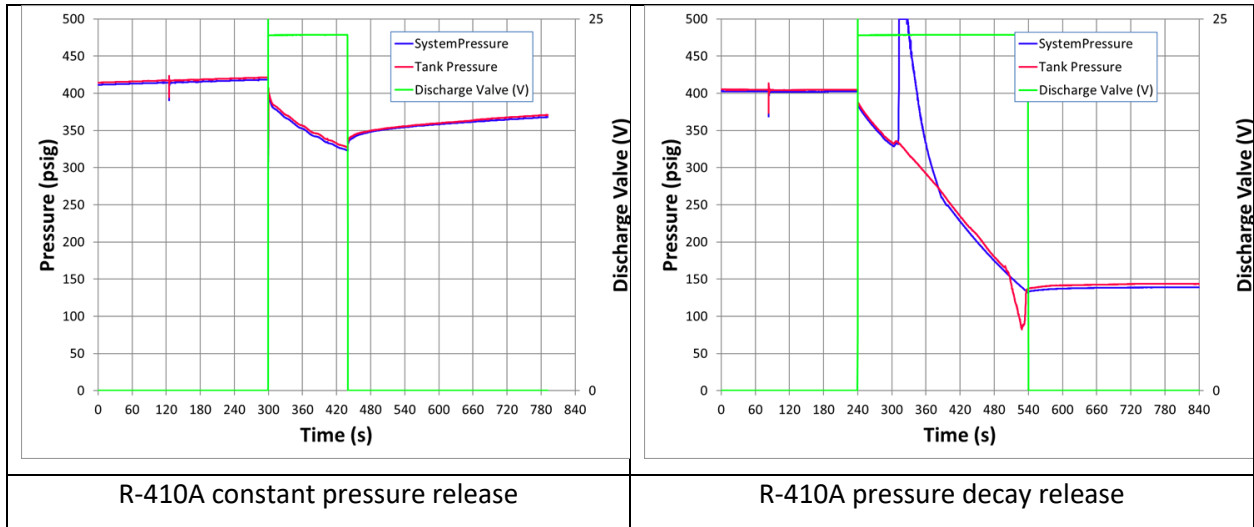


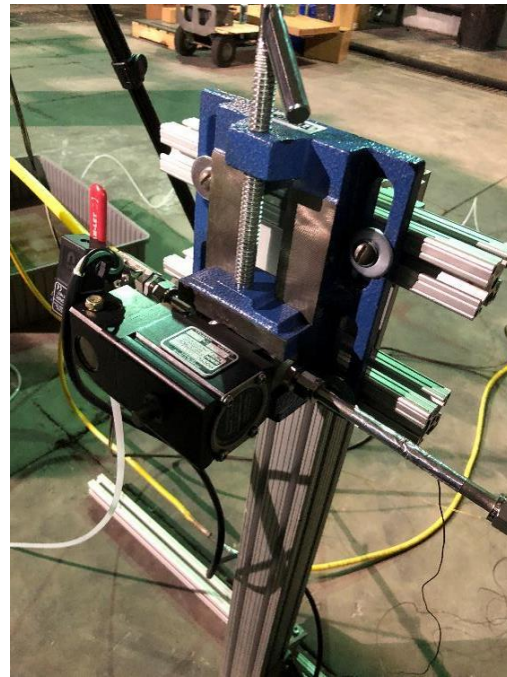
Figure 6 – Comparison of pressure changes

7.3.1. Discharge Equipment

Figure 7 shows the recovery tank suspended from a load cell and wrapped in a heating blanket. The heating blanket was needed to achieve the desired pre-test pressure. The right side of this figure shows one of two electrically piloted, air-operated valves. The valves are of a normally closed design. The valve shown is the discharge valve. Not shown is a similar valve located near the recovery tank used as a safety shut-off if needed. Signals from these devices were routed to the high-speed data acquisition system for recording.



Tank Weighing and Heater Blanket



Air-operated release valve

Figure 7 – Refrigerant Release System

7.4. Data Acquisition Systems

Multiple data acquisition systems were used in this project to facilitate data acquisition from a range of instruments used in this investigation. Starting times for each of these coordinated such that the data could be aligned across all three systems.

An Open Path FTIR analyzer (MIDAC Corporation) with its own data acquisition system was used to record and analyze for the presence of hydrogen fluoride (HF) and hydrogen iodide (HI). The open path FTIR results are quantified if the path length and the gas mixture is known. In this set-up the path length was not available. Assuming, that the path length is similar for the different refrigerants, the data was used to elicit concentrations relative to that of R-410A tests.

The second data acquisition system was a National Instruments system supporting up to 128 thermocouple channels and 64 voltage inputs. The data acquisition rate was selectable up to 1000 Hz. The rates chosen for this project included 1 Hz (Scenario 5) and 10 Hz (All other scenarios).

The third data acquisition system from Fluke was used for monitoring the velocity, temperature, and gases to calculate heat release rates. This system records oxygen, carbon monoxide, carbon dioxide gases along with velocity and temperature. Heat Release rate is calculated according to the information contained in ASTM E2067, “Standard Practice for Full-Scale Oxygen Consumption Calorimetry Fire Tests.”

7.5. Measurements

The instrumentation requirements varied for each of the scenarios. Table 2 lists the types of measurements deployed. Exact details are provided in the description of each scenario.

Table 2 – Instrumentation common to all scenarios

Measurement	Method/Instrumentation
Heat release rate	Oxygen consumption method - O ₂ CO, CO ₂ concentration - Exhaust flow rate Oxygen Sensor: Siemens Oxymat 6 CO/CO ₂ Sensor: Siemens Ultramat 23
Heat Flux	Schmidt-Boelter heat flux gauges 0-50 kW/m ² Medtherm Corp. model 64-5SB-20
Gases	HF and HI (Open Path FTIR), MIDAC Corporation M4411-F
Acid Gases (hydrogen fluoride, hydrogen iodide)	Sample gases pulled through bubblers and processed post-test with ion selective electrode concentration measurements (Thermo Scientific Orion 9609BNWP, 9653BNWP, and A214)
Video Cameras	Crazyfire HZ-100P/SDI
Refrigerant Discharge Rate	Load Cell Systems LST2-100 (0-100 lbm)
Video	Up to 16 channels UVST model Magic U16-4M

7.5.1. Uncertainty of Gas Measurement (Open Path FTIR)

The open path FTIR instrument was able to detect the presence of Hydrogen Fluoride (HF) gas, but the absolute accuracy and uncertainty could not be assessed due to several factors including the following:

- Concentrations of HF in the beam path were not homogeneous, higher in some locations and non-existent in other areas.
- The infrared (IR) beam may not have passed through the region containing the highest overall concentration.
- The instrument could not be calibrated due to the hazard represented by introducing a uniform concentration of HF in a large laboratory.
- The velocity of air passing through the IR beam could not be determined making calculations of total HF production speculative at best.

Despite these issues, the instrument was useful in providing relative comparisons between the HF concentrations resulting from combustion of the refrigerants.

7.5.2. Ion Selective Electrode Measurements

Similar to the open path FTIR instrument, the use of the ion selective electrode (ISE) method was subject to several uncertainties. See Appendix E, Appendix F, and section 10, Testing for Surface Contamination for further discussion on this method. The measurement method concentrates on measurement of the collected water sample. There are other issues associated with the collection of the liquid sample including the following:

- The aspirating sample probe consisted of 7 sample ports evenly spaced at 5 inch intervals. The resulting gas sample represented an average of the concentration sampled air.
- Due to turbulence from fires, the sample probe may not have been drawing samples at the point of highest or average HF concentration.
- Total flow rate of air past the sample probe could not be determined meaning that total production of HF or HI could not be estimated.
- Highest concentrations of HF were obtained from the post-test flush of the sample lines. This showed significant precipitation of acid gas on the walls of the sample lines.
- It was found after all tests had been completed that additional flushing of the gas sampling lines was needed to completely purge that sampling lines. The need for additional flushing also indicates that some amount of acid gas was not collected in the sample bubblers.
- This lack of adequate flushing lead to a biased sample in subsequent tests. This is most observable in Scenario 4 (see Figure 54 – Scenario 4 HF Concentrations (Bar Chart)Figure 54).

The estimated uncertainty of the collected liquid sample is $\pm 20\%$ ($k=1$), but the other factors (above) affecting total uncertainty could not be estimated.

8. Task 1 - Plan, construct, and acquire equipment, refrigerants, and refrigerant release method

Task 1 involved detailed planning and preparation for the testing. Activities in this task included the following:

- Fire test room design and construction
- Test equipment and refrigerants acquisition
- Development of detailed test procedures for Scenarios 1 through 4
- Development of a safety plan

The test setups and its construction used in this investigation are described for each of the test scenarios following. The test and safety procedures are attached in in Appendices [A](#), [B](#), [C](#), and [D](#). AHRI members contributed the refrigerants and HVAC equipment used in this investigation.

8.1. Refrigerant Release Method

The Refrigerant release method was developed to provide and measure the refrigerant release during the tests with a target of an initial flow rate of 50 g/s. A schematic of the test arrangement is provided in Figure 8.

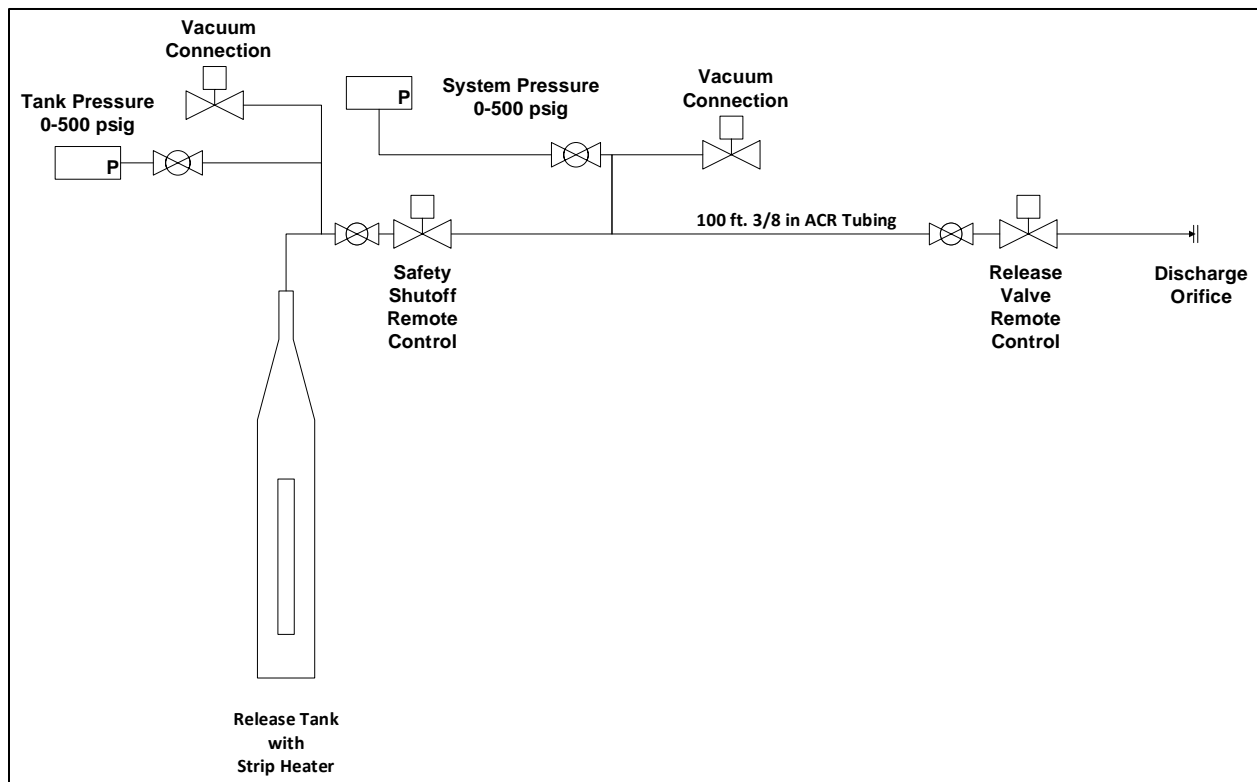


Figure 8 – Schematic of Refrigerant Release Test Arrangement

As shown in Figure 7 the refrigerant tank was suspended from a load cell and wrapped in a heating blanket. Since the tank contents were in a two-phase state, thermocouples were used to establish the initial tank pressure using a PID controller.

Orifices of various sizes were used to determine an orifice size and refrigerant tank pressure that yielded an initial flow rate of 50 g/s (6.6 lbm/min). Table 3 shows the results of testing. In order to prevent routine changing of orifices, a 1.2 mm (0.047 in.) orifice was selected for use in all discharges except in Scenario 5 which had an initial requirement of 30 g/s (4.0 lbm/min). The details are discussed in Scenario 5.

Table 3 – Orifice Size and Tank Pressure resulting in initial 50 g/s discharge rate

Refrigerant	Constant Pressure or Pressure Decay	Orifice Size mm (in.)	Pressure (psig)
R-410A	Constant	1.2 (0.047)	460
	Decay	1.2 (0.047)	411
R-454B	Constant	1.3 (0.052)	337
	Constant	1.2 (0.047)	450
	Decay	1.2 (0.047)	449
R-466A	Constant	1.2 (0.047)	343
	Constant	1.3 (0.052)	246
	Decay	1.2 (0.047)	336
R-32	Constant	1.3 (0.052)	306
	Constant	1.2 (0.047)	459
	Decay	1.2 (0.047)	459



9. Scenario Tests

This section discusses the testing environment and provides a comparison of the test results for each scenario. Greater detail for each of the tests is provided in the appendices.

1. Scenario 1: Comparison and contribution of A1 and A2L refrigerants relative to heat and gases generated in an open flame.
2. Scenario 2: Hazards during suppression activity from change in fire dynamics in the hallway where firefighters may be advancing towards the fire room with a forced refrigerant release in ventilation-controlled conditions.
3. Scenario 3 (Optional): Similar to Scenario 2 with refrigerant release due to system failure in the fire. (Not conducted since Scenario 2 met the overall objectives for the fire service.)
4. Scenario 4: Hazards in fire room during overhaul activity if firefighters action results in a refrigerant line break.
5. Scenario 5: Fire conditions in a below grade closed room without any air movement, having an excessive amount of refrigerant pooling, well above the allowable limits of refrigerant to demonstrate how refrigerant burns when ignited with a flame.

9.1. Scenario 1

Scenario 1 was designed to compare the contributions of A1 and A2L refrigerants relative to heat and gases generated in an open flame.

9.1.1. Test Setup

A three-sided room was constructed under the exhaust hood as shown in Figure 9. The three sides were constructed using gypsum wall board installed on wood support. The back-wall width was 12 feet and the side walls were 8 feet length. The height of each wall was 8 feet.

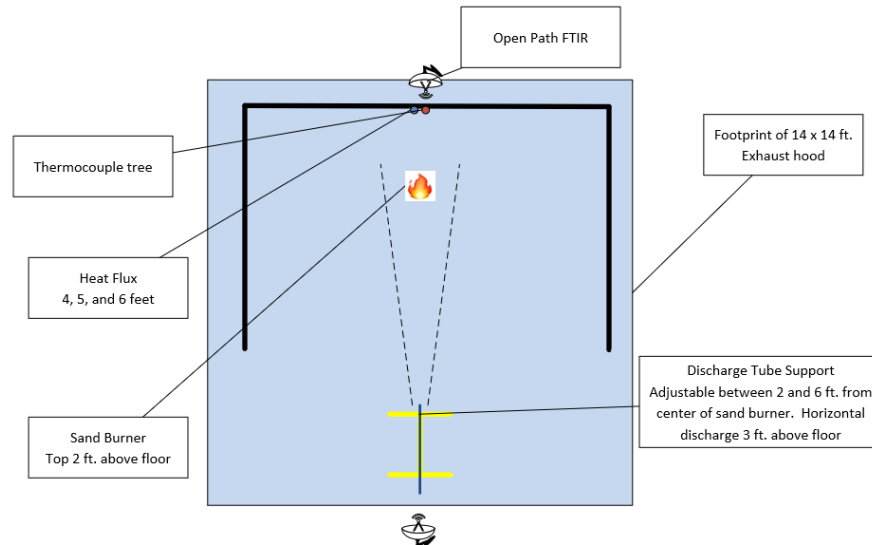


Figure 9 – Schematic layout of Scenario 1 instrumentation and equipment

Figure 10 shows the vertical arrangement of the instrumentation for Scenario 1.

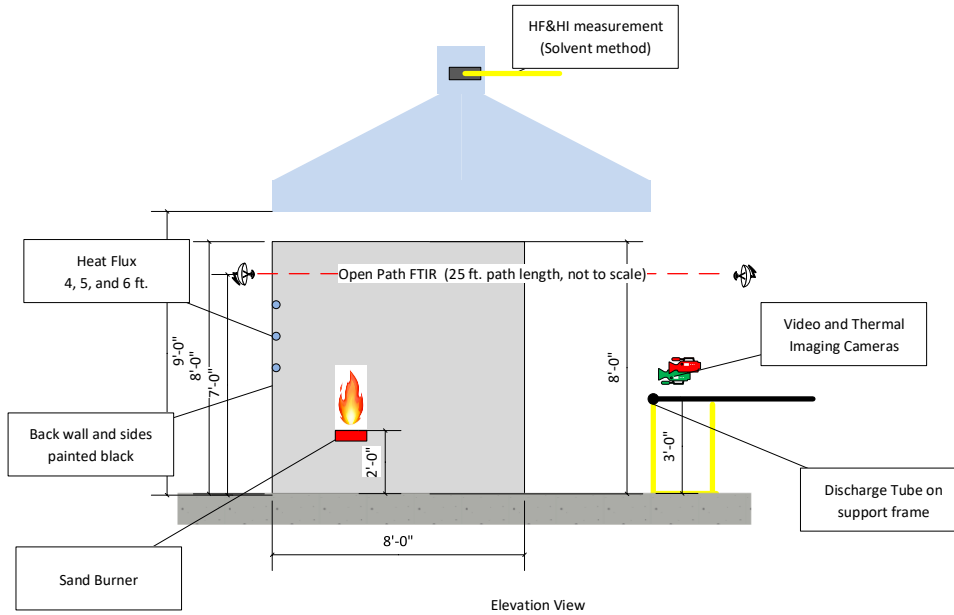


Figure 10 – Schematic layout of Scenario 1 (Elevation View)

Figure 11 shows the sand burner operating with a propane-fueled 120 kW fire. The sand burner was 12 in. square and 4 in. deep. It was located two feet above the floor and 2 feet from the back wall. Heat flux gauges were located on the centerline of the back wall at 4, 5, and 6 feet in elevation. A thermocouple tree of 8 bare beads (18-gauge) was placed 4 in. away from the back wall and 1 in. off the centerline so as not to interfere with the Open Path FTIR beam. The FTIR beam receiver was placed behind the wall to protect it from heat and gases. For additional protection, an IR transparent window was placed in the path length at the 7-foot level on the centerline.

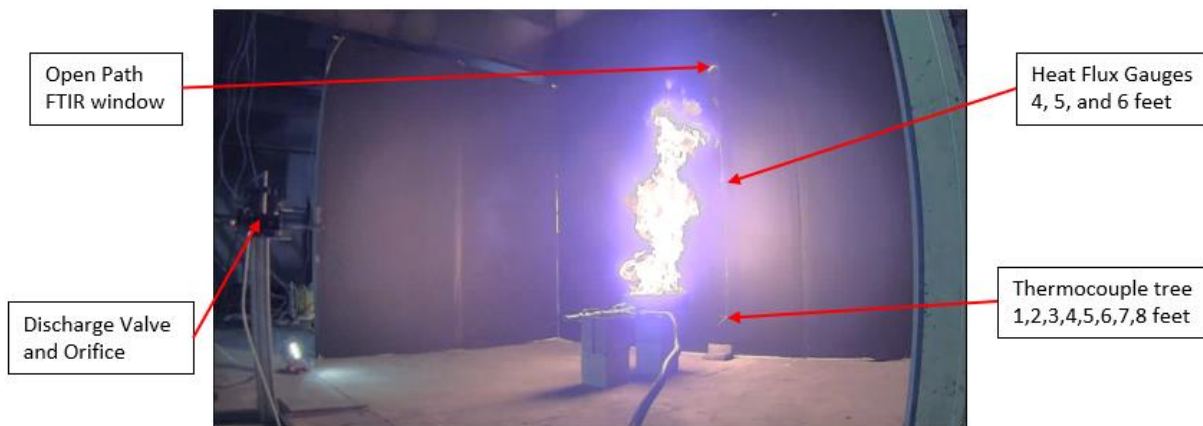


Figure 11 – Scenario 1 Sand Burner and instrumentation

Figure 12 is a view from the floor looking up to the top of the exhaust hood showing the location of the acid gas sample probe on the centerline of the hood. The probe was a 3/8 in. stainless steel tube closed on one end and connected to sample tubing outside of the square plenum box. There were seven equally spaced holes along the length of the tube with each hole sized such that flow through each hole

are equal. The probe was parallel to the discharge flow shown in Figure 9. Because the acid gases react with stainless steel, a heat exchanger (not shown) was installed just outside the plenum box to cool the collected gases and allow a transition to PTFE tubing to minimize the loss of acid gases due to acid-metal reactions.



Figure 12 – Top of exhaust hood showing the acid gas probe

Figure 13 shows the acid gas collection system. Tubing is routed down to the floor level from the probe in the collection hood. A sample pump pulls 0.5 L/min through the two bubblers that are connected in series. With good capture, it is expected that little or no acid gas will be collected in Bubbler 2. In addition, a backflush system was installed such that any gases that condensed on the tube walls can be collected after the test is complete. (However, the volume of backflush may have been insufficient to recover all acids from the sample tubing. Future work should confirm sufficient flushing volume by taking additional measurements between test runs, to confirm that “blank runs” result in collecting zero acids.) The sample pump is operated from the control room allowing for the duration of collection to be matched with the duration of the refrigerant discharge.

A detailed description of this method is included in Appendix E.

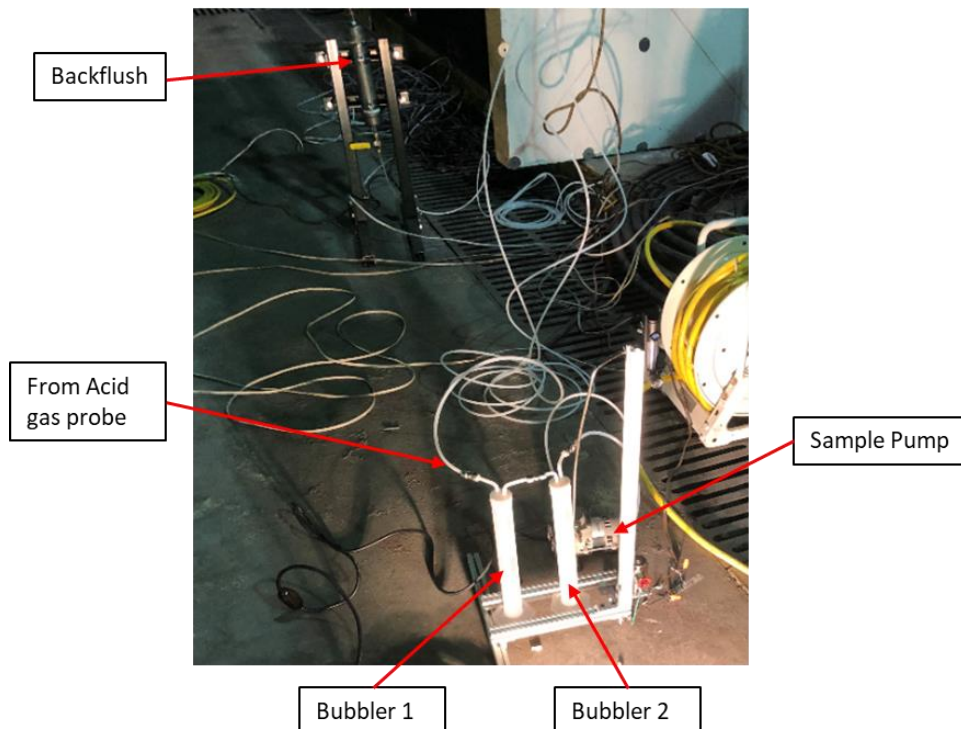


Figure 13 – Acid Gas Collection

9.1.2. Test Procedure

The test procedure in this scenario consisted of the following generalized steps:

- Check that all instruments and data acquisition system are operating;
- Refrigerant release tank filled and heated to the correct pressure;
- Video cameras positioned as needed including view of marquee showing test parameters;
- Heat Release Rate Calorimeter operating;
- Valve alignment is verified and flows adjusted;
- Ignite the sand burner and set to 120 kW Heat Release Rate;
- Release refrigerant after the sand burner has stabilized (140 seconds for constant pressure discharges and 240 seconds for pressure decay discharges);

- Stop data recording 2 minutes after the end of the release and turn off the sand burner;
- Monitor acid gas conditions for safe concentrations prior to entering the lab; and
- Collect bubbler liquid samples and label for post-test analysis.

A full description of the Scenario 1 test procedure is contained in Appendix A.

Testing was conducted with four refrigerants: R-410A, R-32, R-454B, and R-466A. R-410A and R-466A are A1 refrigerants while R-32 and R-454B are A2L refrigerants. Tests were performed using constant pressure and natural pressure decay discharge methods. The test data were obtained with refrigerant release distances of 2 and 6 feet from the front edge of the sand burner.

The testing of R-466A was stopped when it was discovered that the smoke abatement systems was not able to remove iodine from the exhaust stack. During the testing of R466A, pink smoke was visually observed and videotaped emanating from the smokestack of the smoke abatement system. Any future testing involving potential stack release of elemental iodine will be examined for compliance with UL's stack effluent permits.

9.1.3. Results

Visual Observations

Figure 14 shows still frames during the discharge using the constant pressure method. The orifice was located 6 ft. from the front of the sand burner operating at 120 kW. There were no visible signs of additional flaming from the passage of refrigerant through the flames. Pressure decay releases at the 6 ft. distance showed similar behavior during the initial discharge period.

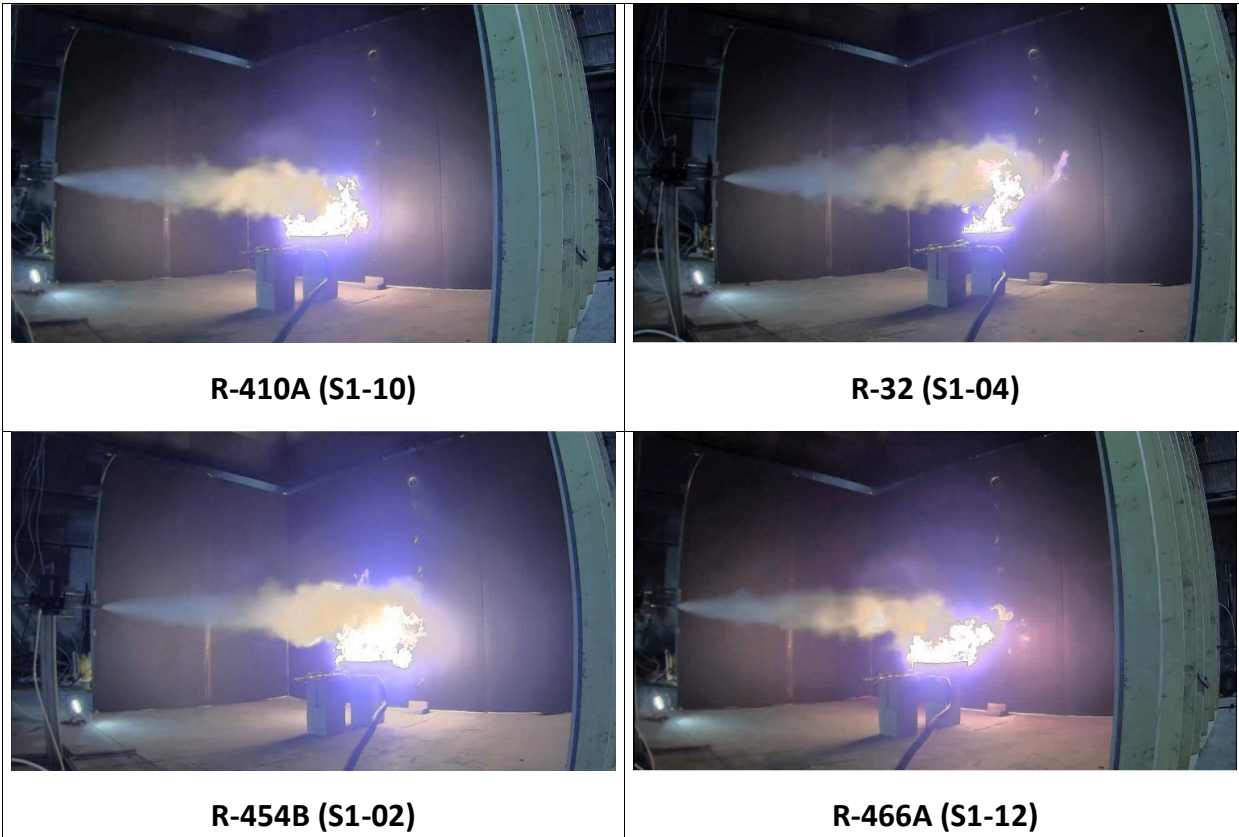


Figure 14 – Constant Pressure Discharges at 6 ft. from the 120 kW Burner

Figure 15 shows the appearance of the discharge about two minutes after the start of the discharge. Notice that the mist has nearly disappeared, but the burner flame is still blown over by the discharge. Shortly after these frames, the mist disappears from the camera view because the discharge is entirely vapor.

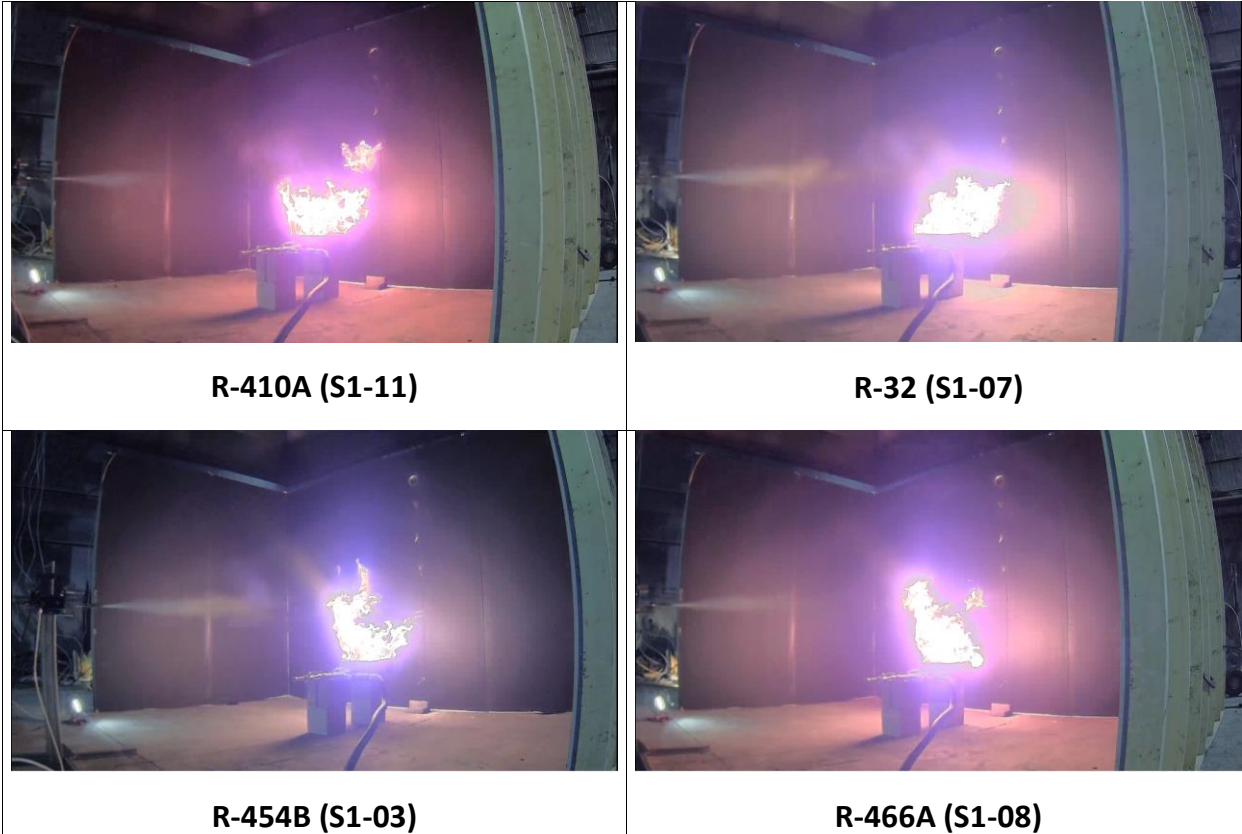


Figure 15 – Pressure Decay Discharges at 6 ft. from the 120 kW Burner

Figure 16 shows still frames during the discharge using the pressure decay method. The orifice was located 2 ft. from the front of the sand burner operating at 120 kW. There were no visible signs of additional flaming from the passage of refrigerant through the flames.

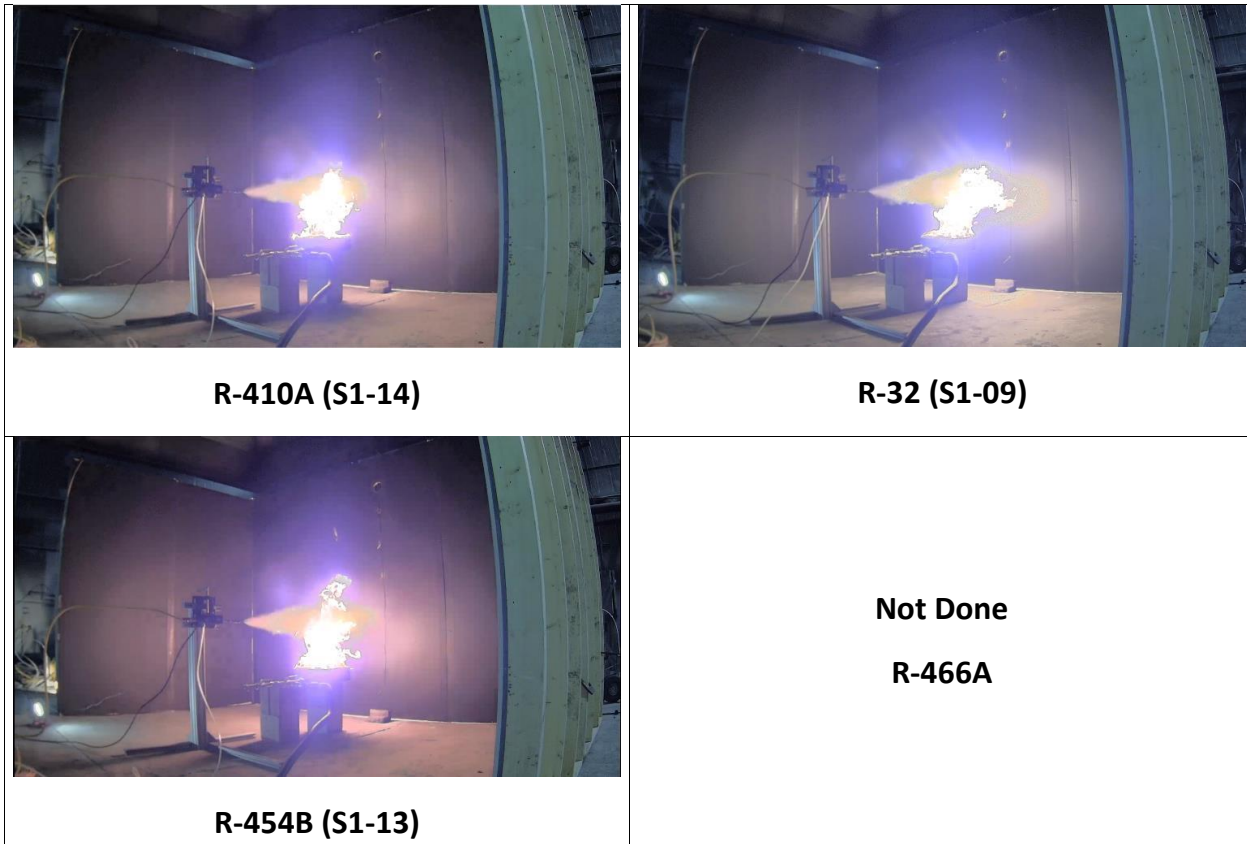


Figure 16 – Pressure Decay Discharges at 2 ft. from the 120 kW burner

Temperatures at the wall

The refrigerant discharges all pushed through the flames pushing the plume closer to the back wall. Figure 17 and Figure 18 shows the temperatures recorded during the constant pressure and pressure decay tests at 6-ft. distance from the sand burner. Throughout the constant pressure tests and during the first part of the pressure decay discharge (at 50 g/s), the temperatures at the 84 and 96 in. level

showed an increase due to the shift of the plume.

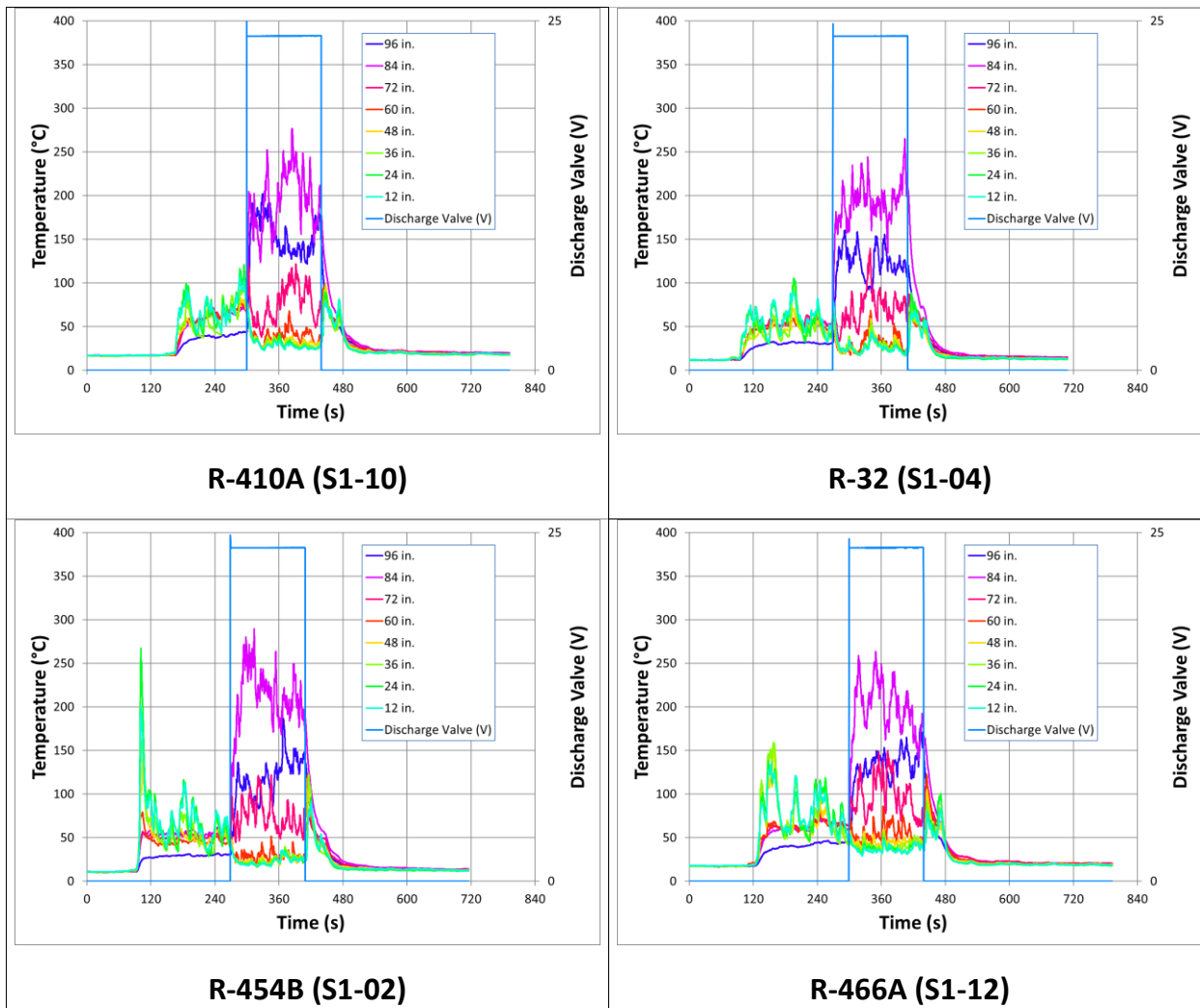


Figure 17 - Scenario 1 Wall Temperatures, Constant Pressure at 6-ft. from sand burner

Once the two-phase flow started, the peak temperatures at the wall shifted down to the 48 and 60 in. level. Temperatures below the top of the sand burner at 12 and 24 in. showed a drop in temperature during the initial discharge which then recovered to pre-discharge levels during the two-phase flow period. This data shows that the fire plume was moved closer to the wall during the discharge. This data is insufficient to say that the fire size had increased. This behavior is similar across all refrigerants tested (A1 and A2L).



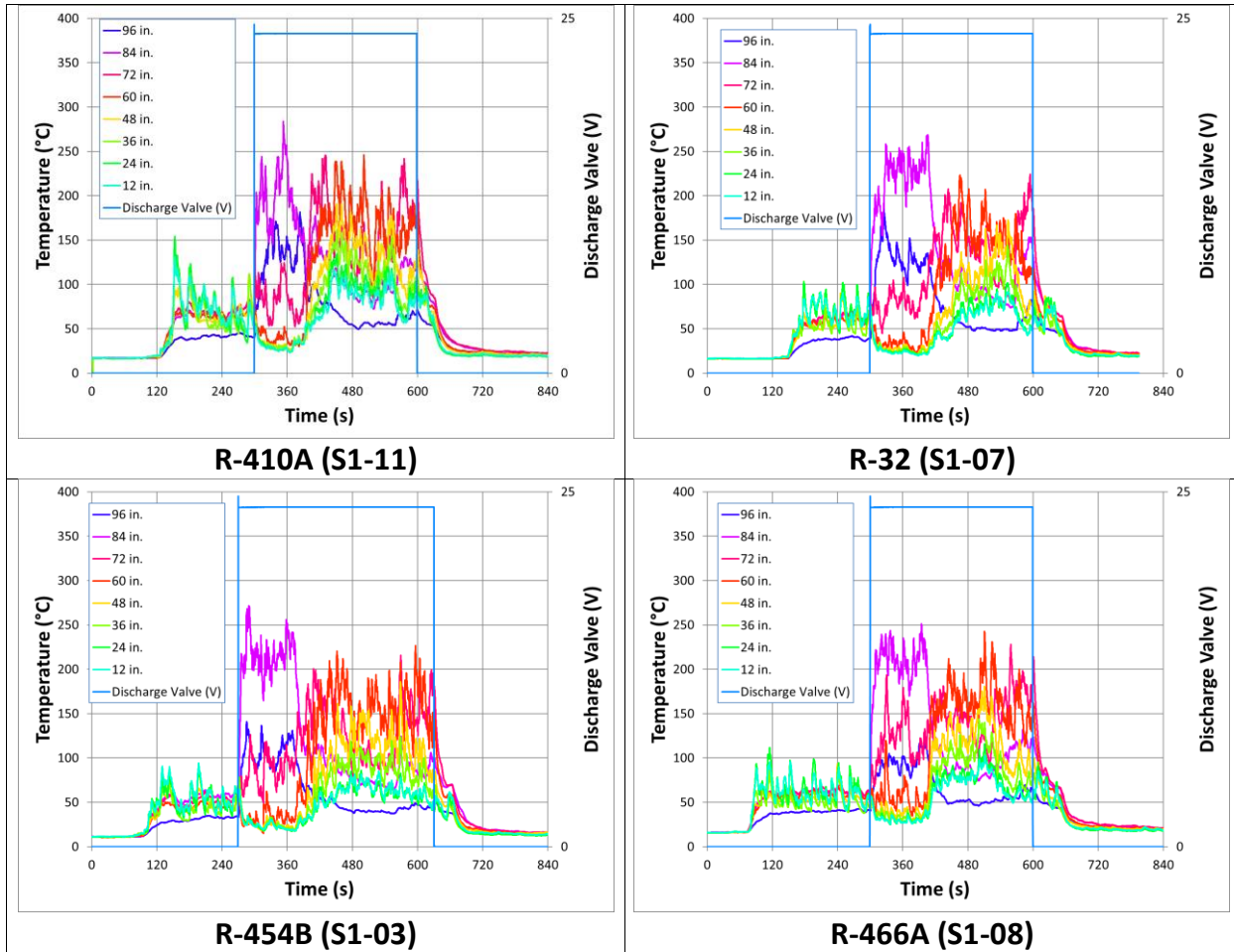


Figure 18 – Scenario 1 Wall Temperatures, Pressure Decay at 6-ft. from sand burner



Figure 19 shows similar data for the pressure decay discharge at the 2-ft. distance. The temperatures were generally lower than the tests at the 6-ft. distance. The temperature at 84 in. shows a similar increase during the initial (50 g/s) release. During the two-phase flow period the peak temperatures shift to the 48 and 60 in. level. In contrast to the 6-ft. tests, the temperatures at the 12 and 24 in. level showed an increase during the initial discharge, then increased further during the two-phase flow period. This data shows that the fire plume was moved closer to the wall during the discharge. The temperatures during the R-32 and R-454B (A2L's) discharges are slightly higher than the R-410A discharges.

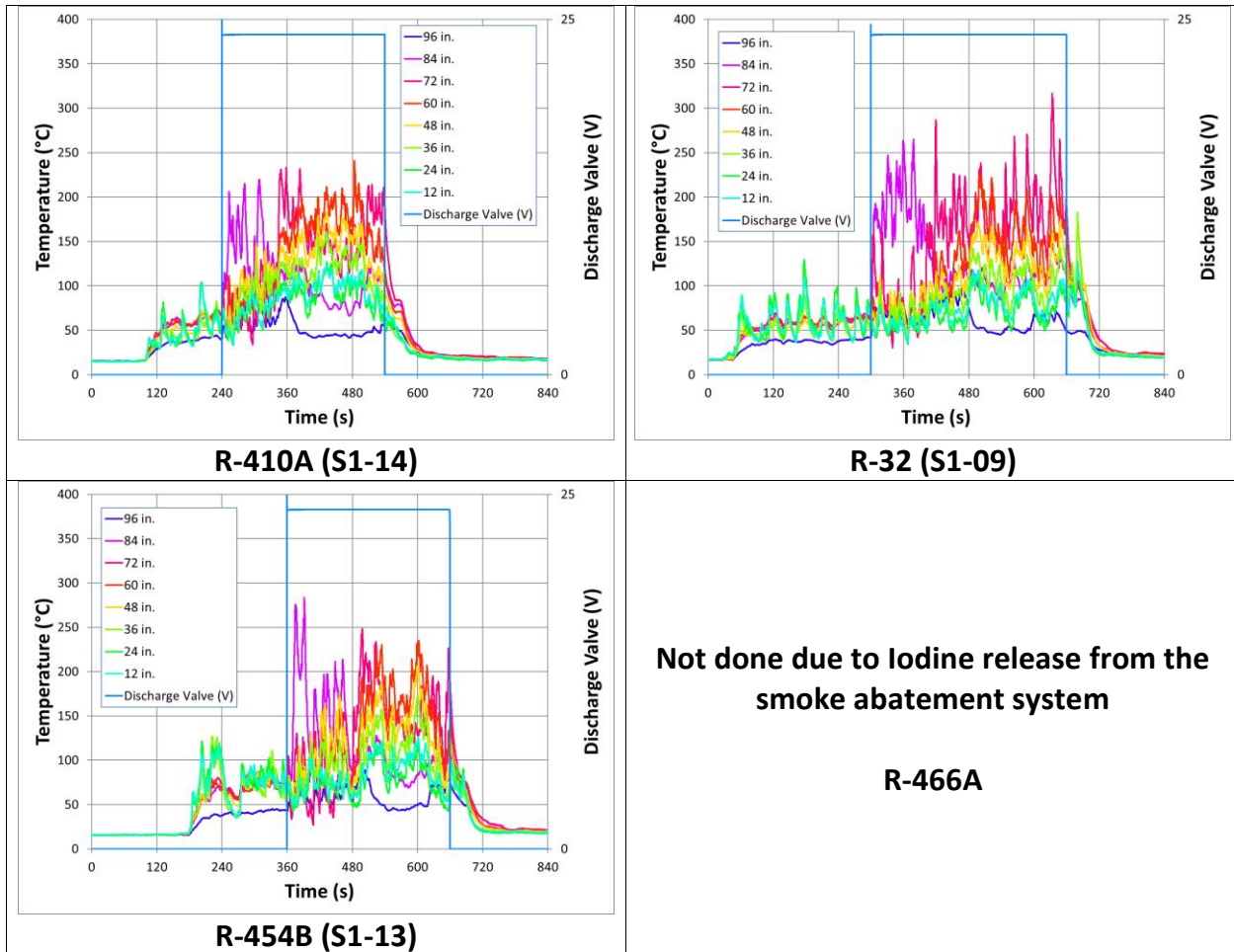


Figure 19 - Scenario 1 Wall Temperatures, Pressure Decay at 2-ft. from sand burner



Heat release rate

The sand burner was set to deliver a 120kW fire throughout each test. The burner flame was ignited and allowed to stabilize before the refrigerant was released. Table 4 groups the tests by leak type and distance from the sand burner. Some of the tests were repeated due to problems with either data collection (high-speed data), video recording, or bubbler sampling. Those problems did not influence the measurement of the heat release rate (HRR).

The table also shows the average HRR while the discharge was in progress. The final column shows the change in HRR during the release over the pre-burn rate. In general, all refrigerants did cause an increase in the HRR, although the photos show the size of the flame is knocked down from its pre-burn size.

Table 4 – Scenario 1 Heat Release Rates

Test#	Refrigerant	Leak	Distance (ft)	Average HRR (kW)**		
				Pre-Release	During Release	Change
S1-10	R-410A	Constant	6	77±6%	165±6%	+88
S1-01	R-410A	Constant	6	115±6%	116±6%	+1
S1-04	R-32	Constant	6	109±6%	134±6%	+25
S1-02	R-454B	Constant	6	141±6%	168±6%	+27
S1-12	R-466A	Constant	6	126±6%	192±6%	+66
S1-11	R-410A	Decay	6	132±6%	170±6%	+38
S1-06	R-410A	Decay	6	143±6%	168±6%	+25
S1-05	R-32	Decay	6	121±6%	143±6%	+22
S1-07	R-32	Decay	6	111±6%	192±6%	+81
S1-03	R-454B	Decay	6	129±6%	164±6%	+35
S1-08	R-466A	Decay	6	115±6%	148±6%	+33
S1-14	R-410A	Decay	2	102±6%	183±6%	+81
S1-09	R-32	Decay	2	116±6%	172±6%	+56
S1-13	R-454B	Decay	2	114±6%	174±6%	+60

** The uncertainty shown is based on the standard error of the mean ($62\%/\sqrt{140} = 6\%$ rounded up, $k=1$).



Figure 20 shows the HRR for the five tests conducted at 6 feet distance and with constant discharge pressure. The noise in the data is caused by the calorimeter at the low end of its design range of 0 to 5,000 kW. The measurement error at this low end of the range is $\pm 62\%$ of reading. This is evident in the two R-410A tests shown in the figure. The first test (S1-01) showed a minimal increase, 0.6 kW on average, while the second (S1-10) test showed an increase of 88 kW on average.

For comparison purpose, a complete combustion of 50 g/s discharge of R-32 refrigerant would have resulted in a fire size of 475 kW. The heat release calorimeter used in this investigation was well-equipped to measure any fire greater than 150 kW.

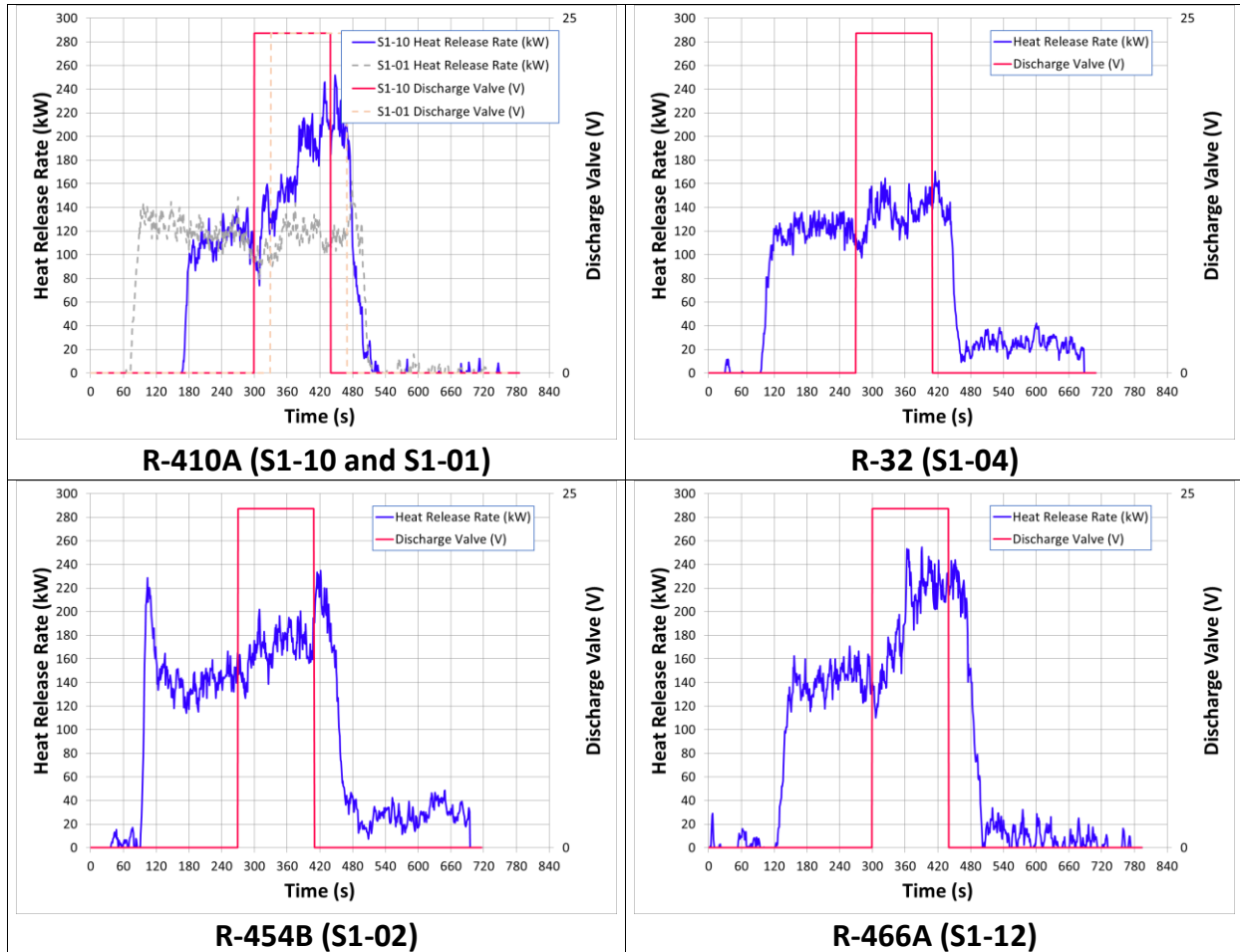


Figure 20 – Scenario 1 HRR at 6 feet distance and Constant pressure

Figure 21 shows the HRR plots for the six tests at 6 feet distance with a pressure decay release. As with the previous figure, the repeat tests highlight some of the variability in measuring low HRR. There is a trend that does show a slight increase in the average heat release rate during the refrigerant release, but only a small fraction (5% to 17%) of the expected HRR for complete combustion of all the R-32 (475 kW).

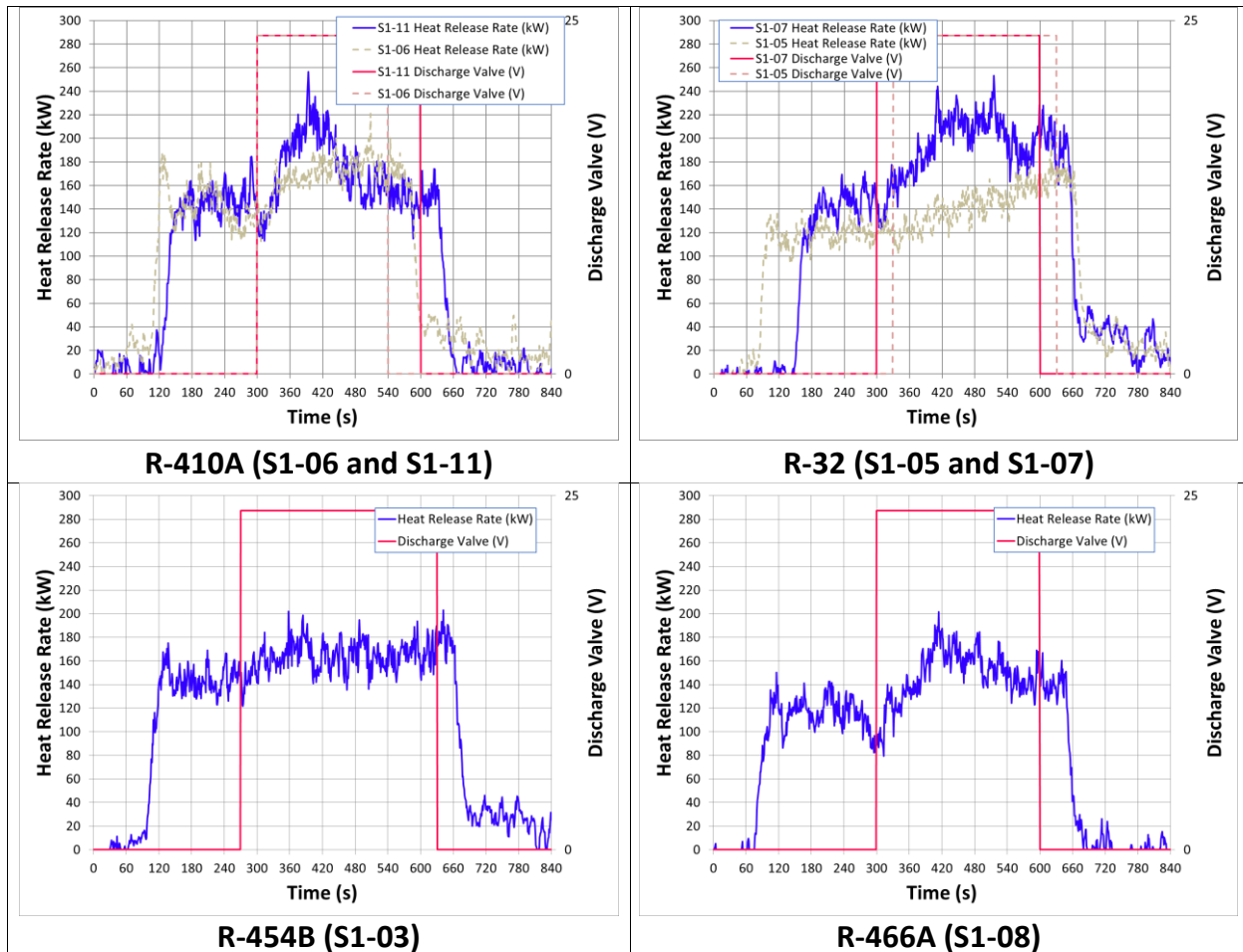


Figure 21 – Scenario 1 HRR at 6 feet with a pressure decay discharge



Figure 22 shows the HRR plots for the releases done at 2 feet distance with a pressure decay release. The data shows that all three of the refrigerants had greater increases in HRR than in the tests done at 6 feet distance. This increase is most likely due to differences in the refrigerant concentration within the jet flow at different distances from the discharge orifice.

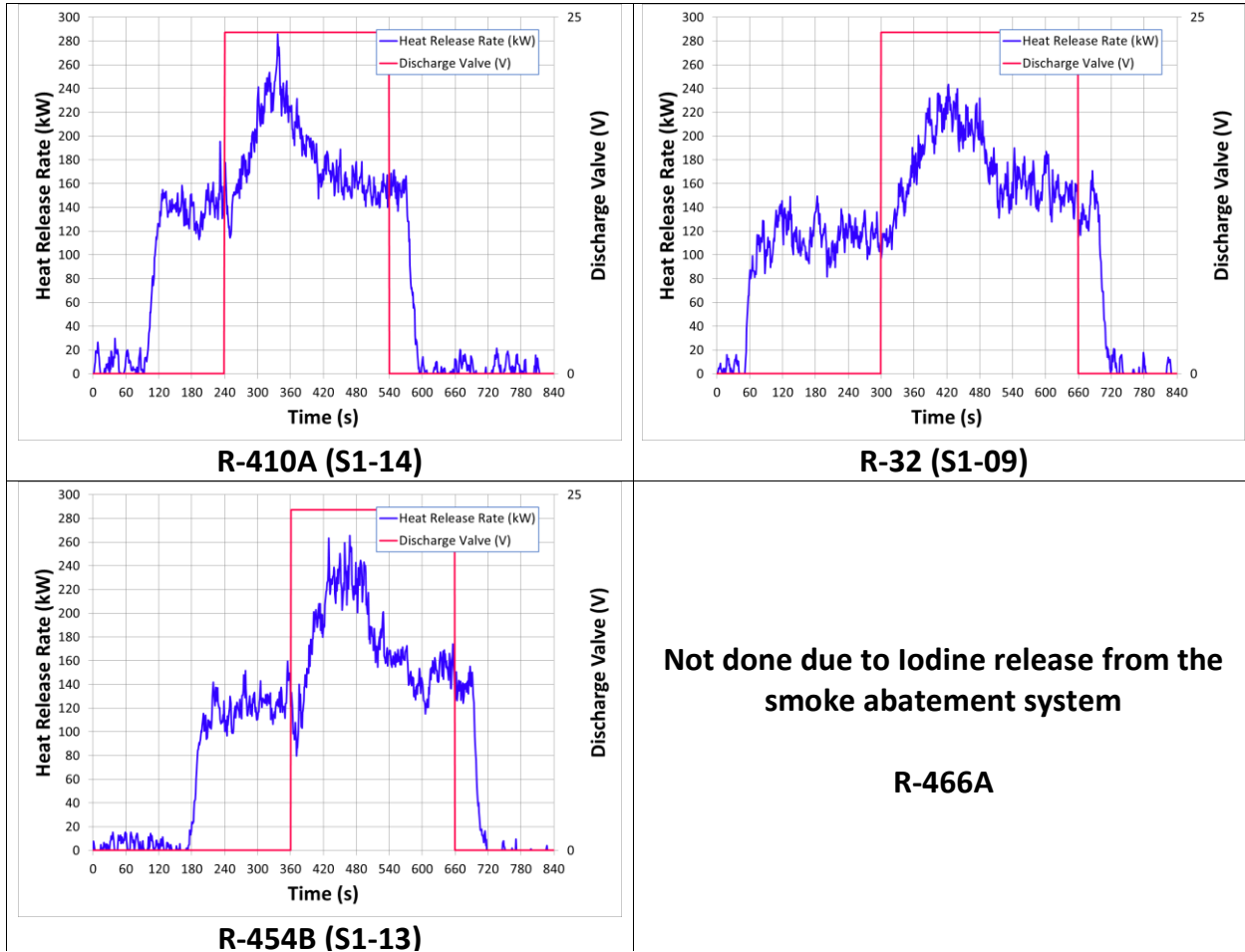


Figure 22 - Scenario 1 HRR at 2 feet with a pressure decay discharge

Figure 23 shows the difference between a constant pressure discharge and a pressure decay discharge. The left side of the figure shows results for R-410A with an initial discharge rate above 50 g/s which then gradually falls to slightly less than 50 g/s. The decrease is due to decreasing pressure in the refrigerant tank, but the pressure has not decreased to the point of causing two-phase flow anywhere but after the discharge orifice. The right side shows a pressure decay that begins similarly slightly above 50 g/s followed by a rapid drop after about one minute due to two-phase flow in the lines upstream before of the discharge orifice. During the two-phase flow region, the mass flow rate drops to less than 10 g/s, The transition from liquid flow to two-phase flow upstream of the orifice does not initially change the orifice velocity very much due to choked flow conditions (velocity is limited to the speed of sound in the refrigerant) or nearly choked flow. Vapor has significantly lower density than liquid, and two-phase flashing flow will accelerate as liquid changes to vapor, so during choked flow conditions the orifice exit velocity will remain approximately constant despite the large drop in mass flow, though as the tank pressure decays towards the end of the release the jet velocity may decrease to some extent.

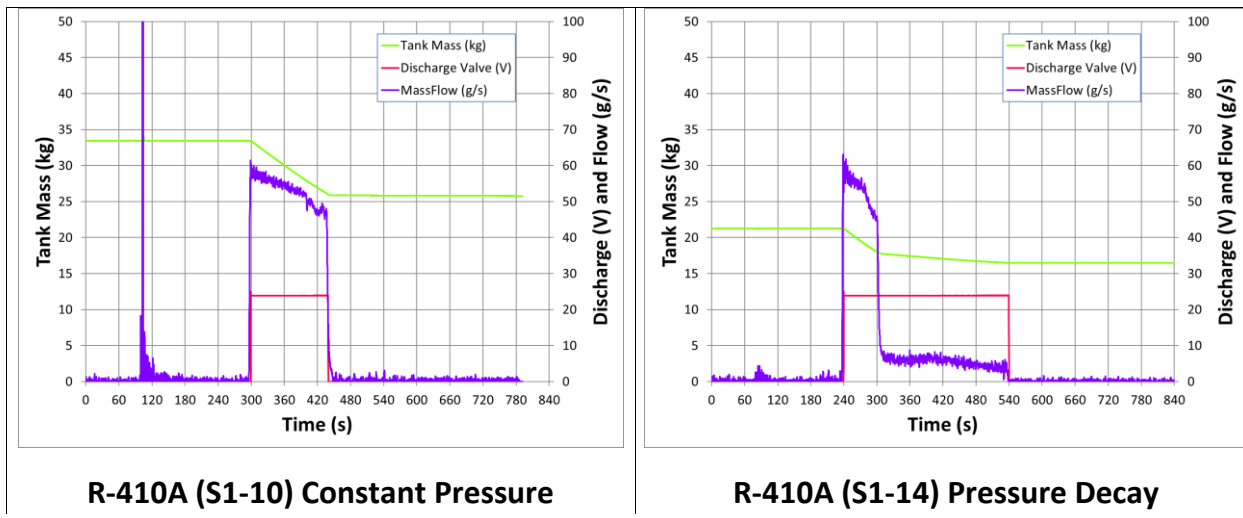


Figure 23 – Comparison of typical constant pressure and pressure decay discharges

Heat Flux

Heat flux was measured at 4, 5, and 6 feet above the floor in the center of the back wall. The sand burner back edge was two feet away from that back wall. The sand burner was started and allowed to stabilize for five minutes before the start of the refrigerant discharge. Figure 24 shows the results from a constant pressure discharge. The data shows an immediate drop in heat flux when the discharge begins. Once the discharge is stopped, heat flux levels return to pre-discharge levels.

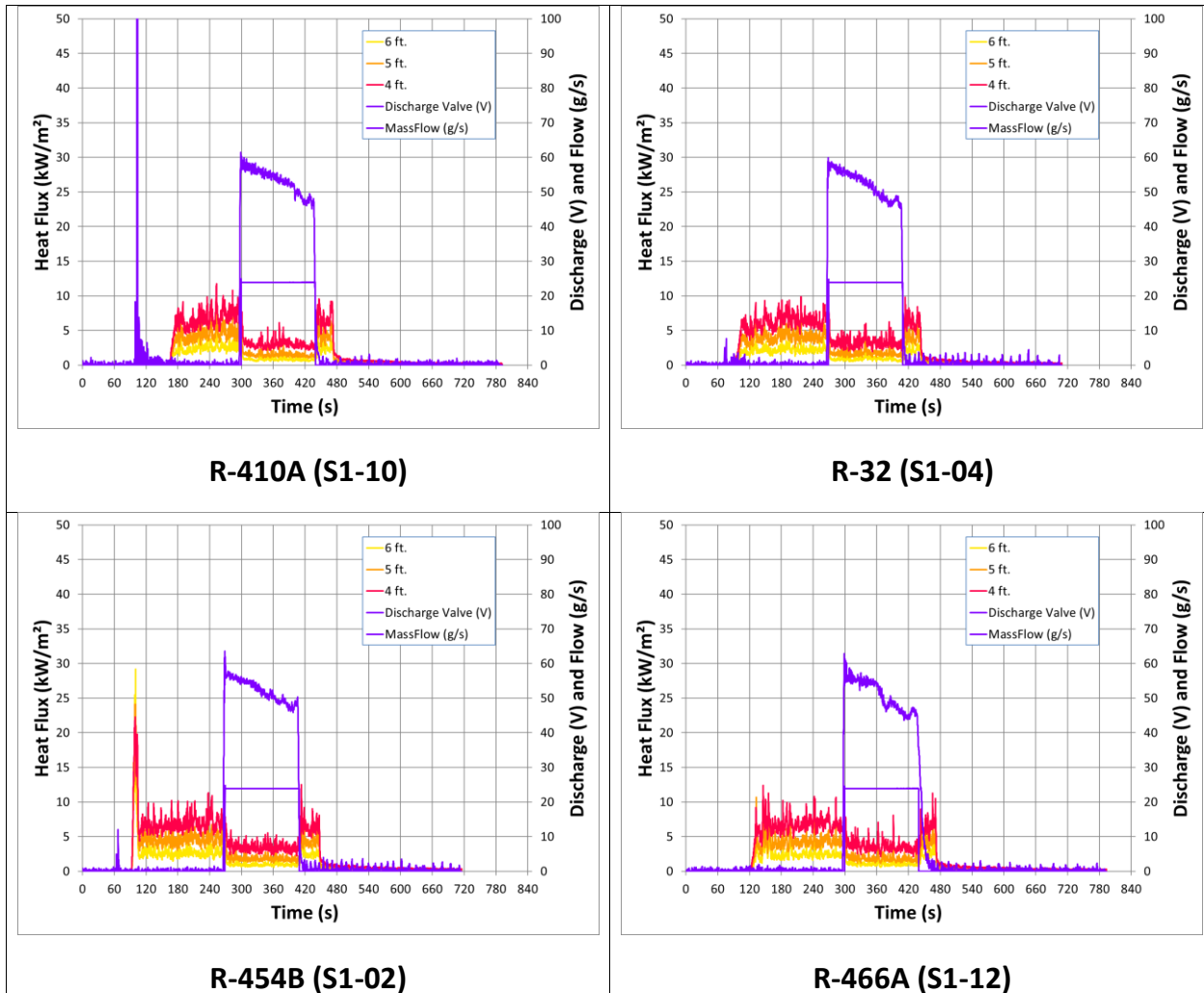


Figure 24 – Scenario 1, Heat Flux Constant Pressure Discharge at 6 ft. from the flame

Figure 25 shows the results using the pressure decay method with the discharge at 6 feet distant from the front edge of the sand burner. All four refrigerants show an immediate drop in measured heat flux as soon as the release begins. Once the two-phase flow begins (after 60-90 seconds), the heat flux returns to pre-release levels, albeit slightly higher.

It was observed that the initial release rate knocked down the visible size of the fire and bent the plume toward the back wall. The immediate drop in heat flux was due to the reduction in radiant heat from the ignition flame. The lower, two-phase, release rate allowed the flame size to recover, but the lower release rate pushed the plume closer to the heat flux gauges. This effect along with the slightly higher heat release rates accounts for the slight increase in heat flux at the 4-foot level (estimated at 2 to 3 kW/m²). There were no significant differences based on the refrigerant selection.

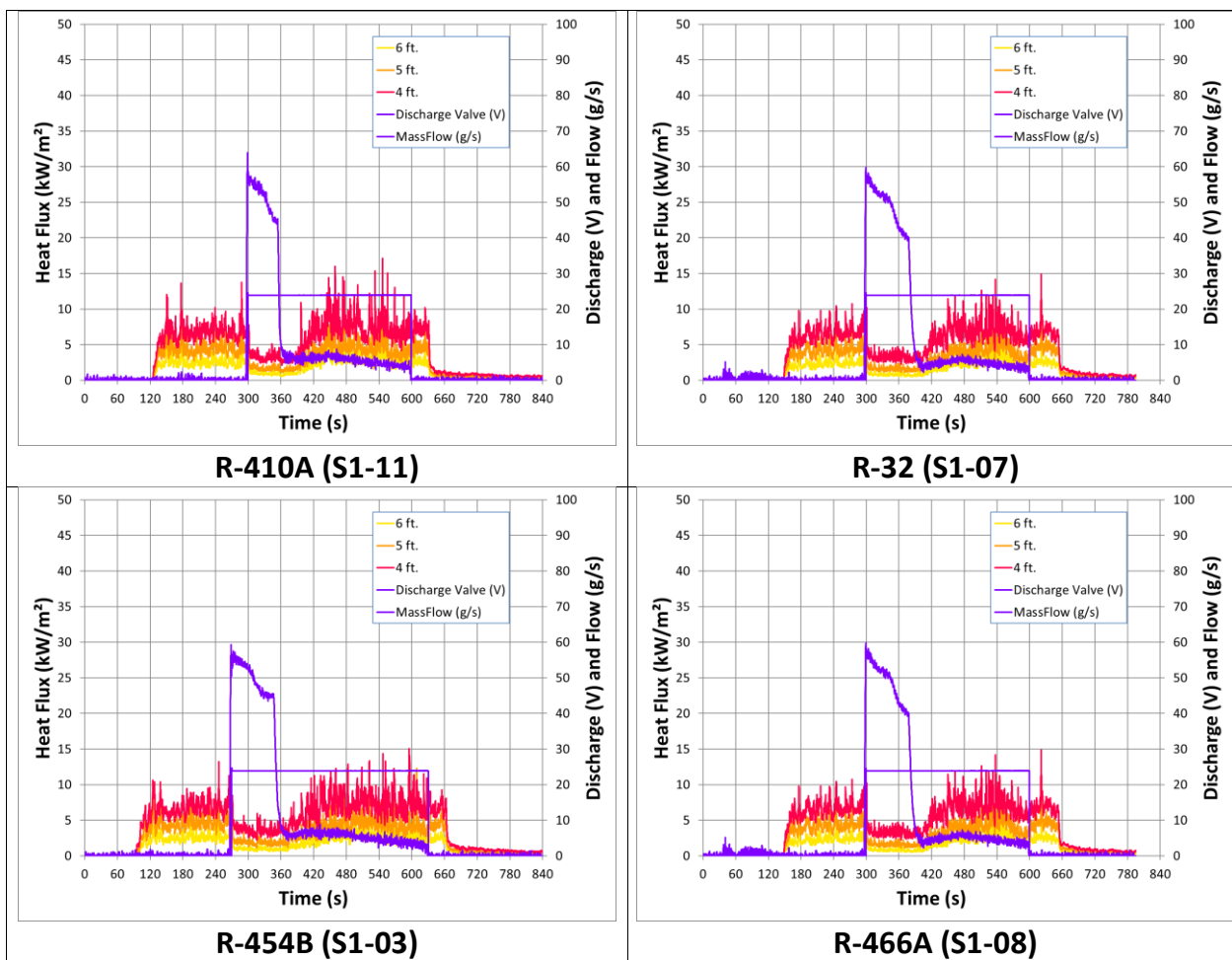


Figure 25 – Scenario 1 Heat Flux with pressure decay discharge at 6 ft. from flame



A similar effect was observed (Figure 26) with pressure decay releases at 2 feet from the front edge of the sand burner. There was a smaller initial drop in heat flux followed by a recovery to pre-release levels. A similar recovery to slightly high heat flux was observed that was independent of the refrigerant selection.

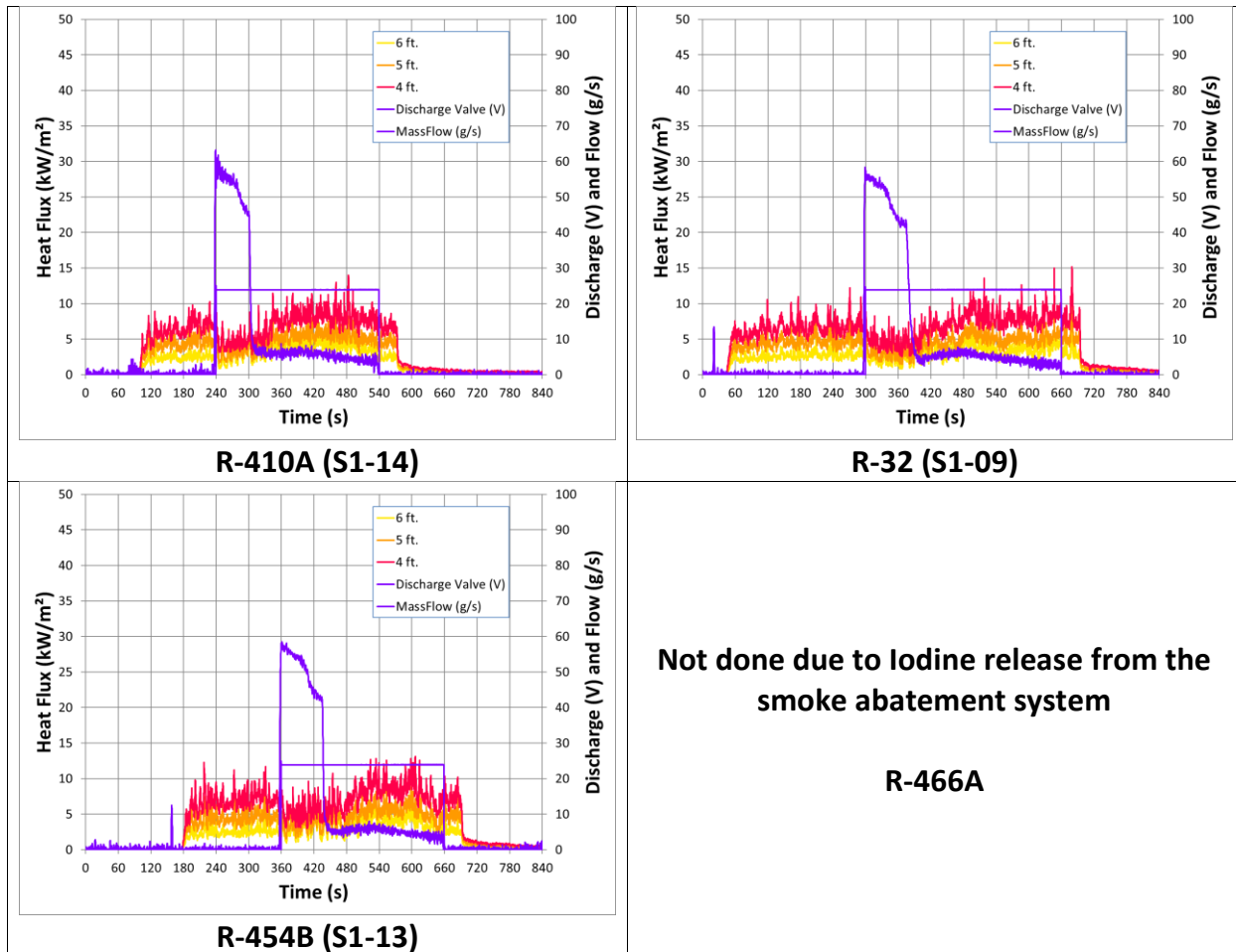


Figure 26 - Scenario 1 Heat Flux with discharge at 2 feet from flame

HF concentration by Open Path FTIR

Table 5 summarizes the Hydrogen Fluoride measurements using the Open Path FTIR data. The equipment detected hydrogen fluoride during the tests.

Since the path length for the open-path FTIR cannot be defined in this scenario, the data is useful for relative comparison between the reference refrigerant (i.e., R-410A) and the other test refrigerants (i.e., R-32, R-454B, and R-466A). In the calculations, it assumed that the path length for the FTIR beam through the gases is constant for each of the refrigerants. The calculated relative peak and average HF concentrations are presented in Table 5.

Table 5 – Scenario 1 Hydrogen Fluoride (HF) Results

Test#	Refrigerant	Leak Type	Distance (ft)	Duration	Peak Relative to R-410A	Average Relative to R-410A
Estimated Uncertainty:					±14%	±2%
S1-10	R-410A	Constant	6	140	1.00	1.00
S1-04	R-32	Constant	6	140	1.11	1.01
S1-02	R-454B	Constant	6	140	0.70	0.91
S1-12	R-466A	Constant	6	140	0.86	1.07
S1-11	R-410A	Decay	6	300	1.00	1.00
S1-07	R-32	Decay	6	300	0.56	0.55
S1-03	R-454B	Decay	6	361	0.80	0.61
S1-08	R-466A	Decay	6	300	1.02	0.79
S1-14	R-410A	Decay	2	300	1.00	1.00
S1-09	R-32	Decay	2	360	1.06	0.71
S1-13	R-454B	Decay	2	299	1.11	0.88

HF concentration values were not calibrated due to unknown path length and can only be interpreted on a relative basis between tests. Tests S1-10, S1-11, and S1-14 were used as the relative references.



The uncertainty shown in Table 5 is based on the comparison of the Standard Error of Concentration (SEC) and the measured concentrations reported by the open path FTIR software. Figure 27 shows a typical plot of these two measures during the time that the refrigerant is released into the open flame. The black dots in the plot are the ratio of the SEC to the measured concentration. Over the period of release this ratio is 0.14 or 14% (k=1). This value is used as the measure of uncertainty for the peak concentration relative to R-410A. The average concentration is based on the number of samples in the (about one sample every three seconds). The standard error of the mean reduces this 14% uncertainty by the square root of the number of samples or $\frac{14\%}{\sqrt{47}} = 2\%$. This error is slightly smaller for the longer duration releases, but still rounds up to 2%.

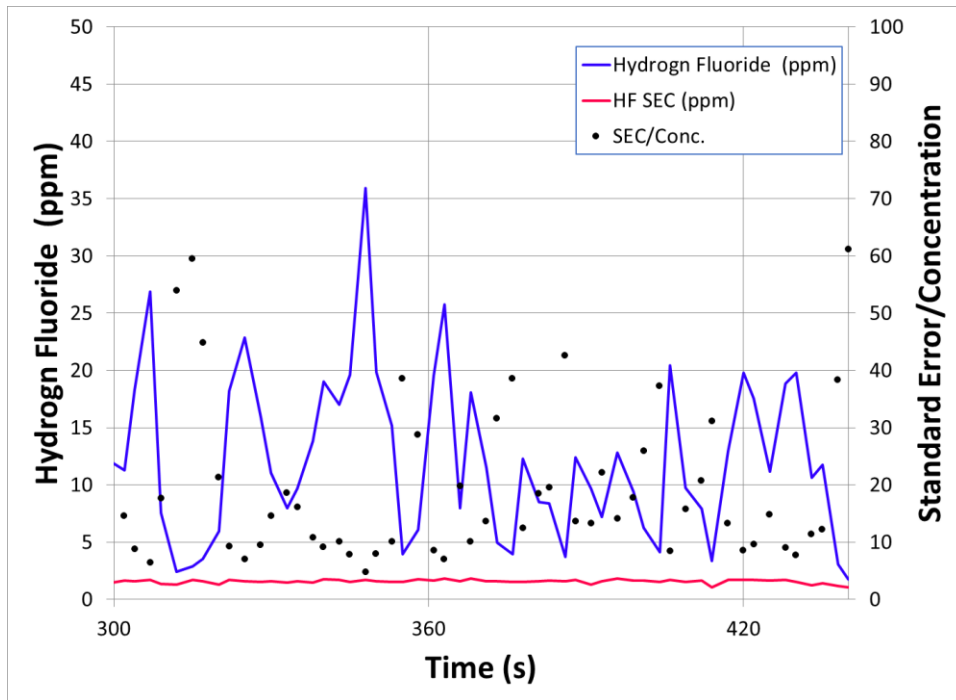


Figure 27 – Typical HF concentration plot during release

Hydrogen iodide (HI) was not detected by the Open Path FTIR in either of the R-466A tests. Figure 28 shows a high standard error of concentration (SEC) due to interference by other gases. The figure compares an R-410A test, where HI was not expected and R-466A where HI might have been expected. Similar high values for SEC were produced in the other R-466A test, S1-08.

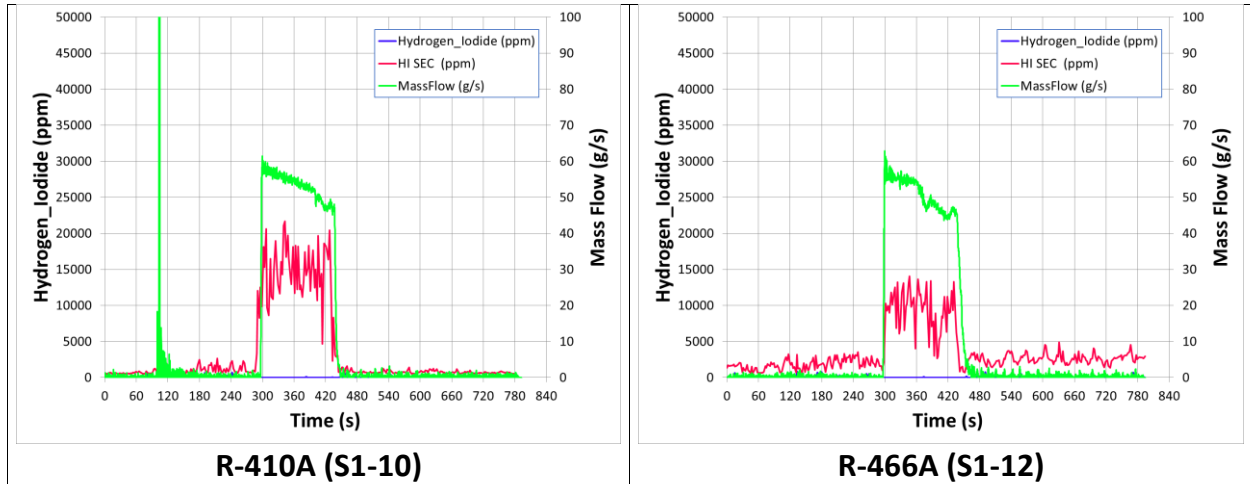


Figure 28 – Standard Error of Concentration (SEC) for Hydrogen Iodide

9.1.3.1. Hydrogen Fluoride Using Aqueous Solution

The bubbler method used to trap acid gases is described in Appendix E, Scenario 1 – Ion Selective Electrode Measurements. In addition to the two bubbler containers, an additional sample was taken post-test by backflushing the sample line from the probe in the hood. This practice was utilized because the acid gases react with water vapor and condense on the sample lines. Significant concentrations of acid gases were found in the backflush samples.

Table 6 displays the exhaust hood concentration derived from the sample probe at the top of the hood (see Figure 12). The table calculates a ratio of concentrations relative to R-410A. The conversion of aqueous concentrations to concentrations at the sample probe is documented in Appendix E.

Table 6 – Scenario 1 Acid Gas Estimate

Test#	Refrigerant	Leak	Distance (ft)	Duration (s)	Average Exhaust Hood Concentration* (ppm, v/v)	Concentration Relative to R-410A
Fluoride (F⁻) Ion Measurements						
S1-10	R-410A	Constant	6	140	156 ^[1]	100%
S1-01	R-410A		6	140	58	37%
S1-04	R-32		6	140	33	21%
S1-02	R-454B		6	140	32	21%
S1-12	R-466A		6	140	177	113%
S1-11	R-410A	Decay	6	300	47 ^[1]	100%
S1-06	R-410A		6	240	37	79%
S1-05	R-32		6	301	4	9%
S1-07	R-32		6	300	42	89%
S1-03	R-454B		6	361	24	51%
S1-08	R-466A		6	300	36	77%
S1-14	R-410A		2	300	121 ^[1]	100%
S1-09	R-32		2	360	43	36%
S1-13	R-454B	2	299	97	80%	
Iodide (I⁻) Ion Measurements						
S1-12	R-466A	Constant	6	140	7	Not Applicable
S1-08	R-466A	Decay	6	300	1	Not Applicable

* -- The measurement uncertainty of these concentrations was ±20% (k=1) excluding the amount HF loss in the collection hood and concentrations remaining in the sample tubing. This additional uncertainty could not be quantified. See section 7.5.2 for discussion.

^[1] – Represents the reference for relative concentrations for all other tests at that distance and discharge duration



Mass Release

The amount of mass released in using the pressure decay method was less than the charge in the tank due to the drop in tank pressure and the transition to two-phase flow. Table 7 summarizes the mass release for all Scenario 1 tests.

Table 7 – Scenario 1 Refrigerant Mass release

Test#	Refrigerant	Leak	Initial Tank Charge (lbm)	Released Mass (lbm)	Percentage of charge released (%)
S1-10	R-410A	Constant	80% liquid fill	16.4	100%
S1-01	R-410A	Constant	80% liquid fill	No Data	No Data
S1-04	R-32	Constant	80% liquid fill	16.3	100%
S1-02	R-454B	Constant	80% liquid fill	16.0	100%
S1-12	R-466A	Constant	80% liquid fill	15.8	100%
S1-11	R-410A	Decay	15	9.7	65%
S1-14	R-410A	Decay	15	10.5	70%
S1-06	R-410A	Decay	15	9.2	61%
S1-05	R-32	Decay	15	12.4	82%
S1-07	R-32	Decay	15	11.3	76%
S1-09	R-32	Decay	15	11.9	79%
S1-03	R-454B	Decay	15	12.4	83%
S1-13	R-454B	Decay	15	11.3	75%
S1-08	R-466A	Decay	15	10.3	69%



9.1.4. Scenario 1 Summary

A summary of the results of Scenario 1 is as follows:

- The large calorimeter used in Scenario 1 had a measurement uncertainty of 62% of reading at the low end (< 150 kW) of this calorimeter's range (0-5,000 kW) for single point measurements. Averages were used to compare baseline fires to increases during refrigerant releases.
- Increases in the rate of heat release (HRR) were relatively small in comparison to the 120 kW sand burner flame. The largest average increase for any refrigerant over the baseline was 88 kW for R-410A, an A1 refrigerant.
- The largest average increase recorded for an A2L refrigerant was 80 kW.
- The Open Path FTIR instrument yielded relative comparisons of hydrogen fluoride gas. The relative average measurement of HF concentration for the A2L refrigerants was at most 1% above that of R-410A and many times, significantly less.
- The open path FTIR instrument did not detect the presence of hydrogen iodide in the tests with R-466A. R-466A FTIR measurements showed similar levels of HF when compared to the other three refrigerants.
- The pressure decay method at 2 feet distance resulted in higher relative concentrations than at the 6 foot distance.

9.1.5. Firefighter Tactical Considerations for A2L Refrigerants Scenario 1

Hazard	Result	Comment
Temperature – Wall	Temperatures increased on the side of the sand burner flame pushed by the discharge.	Temperatures were recorded in the range of 200°C (390°F) at the 60 in. level
Heat Flux – Wall	Heat flux at 4, 5, and 6 ft. decreased from an average of 7 kW/m ² to 3 kW/m ² during the initial discharge, then increased to 8 kW/m ² during two-phase discharge flow.	Heat flux in the range of 3-5 kW/m ² will cause pain to exposed flesh within seconds. Refer to Appendix H for more information.
Heat release rate (HRR)	The average heat release rate increased over the size of the baseline 120 kW fire in the range of 1 to 80 kW. No significant differences were seen comparing A1 to A2L refrigerants.	150 to 300 kW is about the size of a 30-gallon plastic trash can fire. Refer to Appendix H for more information.
Deflagration	No deflagration was observed.	A1 and A2L refrigerants performed in similar manner.
Hydrogen Fluoride (HF) and Hydrogen Iodide (HI) generation	<p>All refrigerants tested generated HF gas at potentially hazardous levels.</p> <p>A2L refrigerants released HF during combustion at levels similar to that of A1 refrigerants.</p> <p>The aqueous solution method showed HF production from A2L refrigerants was slightly less than from A1 refrigerants.</p> <p>HI was seen in small amounts with R-466A, an A1 refrigerant, but this refrigerant produced similar levels of HF.</p>	<p>HI and HF and other halogen compounds are inhalation and skin contact hazards. Contact with contaminated turnout gear can lead to skin or inhalation exposures if not properly cleaned.</p> <p>Fire service personnel need to don appropriate PPE for all phases of operations from suppression, to overhaul, investigation, and recovery.</p> <p>Refer to Appendix G for a further discussion of this hazard.</p>



9.2. Scenario 2

Scenario 2 was designed to represent the hazards during suppression activity from change in fire dynamics in the hallway where firefighters may be advancing towards the room of fire origin when a refrigerant leak occurs under ventilation-controlled fire conditions.

9.2.1. HVAC Equipment

The air handler used in Scenario 2 testing was supplied by an AHRI member. The model number was Goodman's ARUF61D rated at 5 tons of A/C, shown in Figure 29. The unit was installed at a height of 6 feet in the horizontal ceiling orientation without any duct work as was shown in Figure 1. Note the unit had an aluminum round tube plate fin coil.



Figure 29 – Goodman Model ARUF61D 5 Ton Air Handler

9.2.2. Refrigerants

The refrigerants used in this scenario included R-410A and R-32.

9.2.3. Test Setup

A test structure was constructed and located under the calorimeter exhaust hood which allowed for heat release rate measurements and smoke abatement. The test structure consisted of two 14 x 14 x 8-ft high test rooms connected to a 4-ft. wide hallway located between the two rooms. Each test room had a 2.5 ft wide by 7 ft. high doorway connected to the hallway. The two-room structure enabled a quicker turnaround in-between the tests.

The walls and ceiling were covered with two layers of gypsum wall board. Sections of the ceiling and hallway walls and ceiling are covered with additional layers of ½ in. Durock® sheets where heat exposure was expected to be most intense. The floors of the rooms were also covered with Durock® to protect the test facility floor from spalling. The rooms were not painted.

For suppression, the rooms were outfitted with an open sidewall sprinkler. The hallway had an open ceiling mounted sprinkler head. Water flow was initiated as needed from switches in the control room operating water admission valves.

Each room had access openings for test set-up and to enable fire suppression activity after the test was terminated. These openings were fitted to UL Listed fire doors and were kept closed during the test.

The room that is not under test had the hallway exit blocked with an insulated panel with similar insulation to the hallway. The fire test room hallway was open during the test. A plan view of the structure is shown in Figure 30.

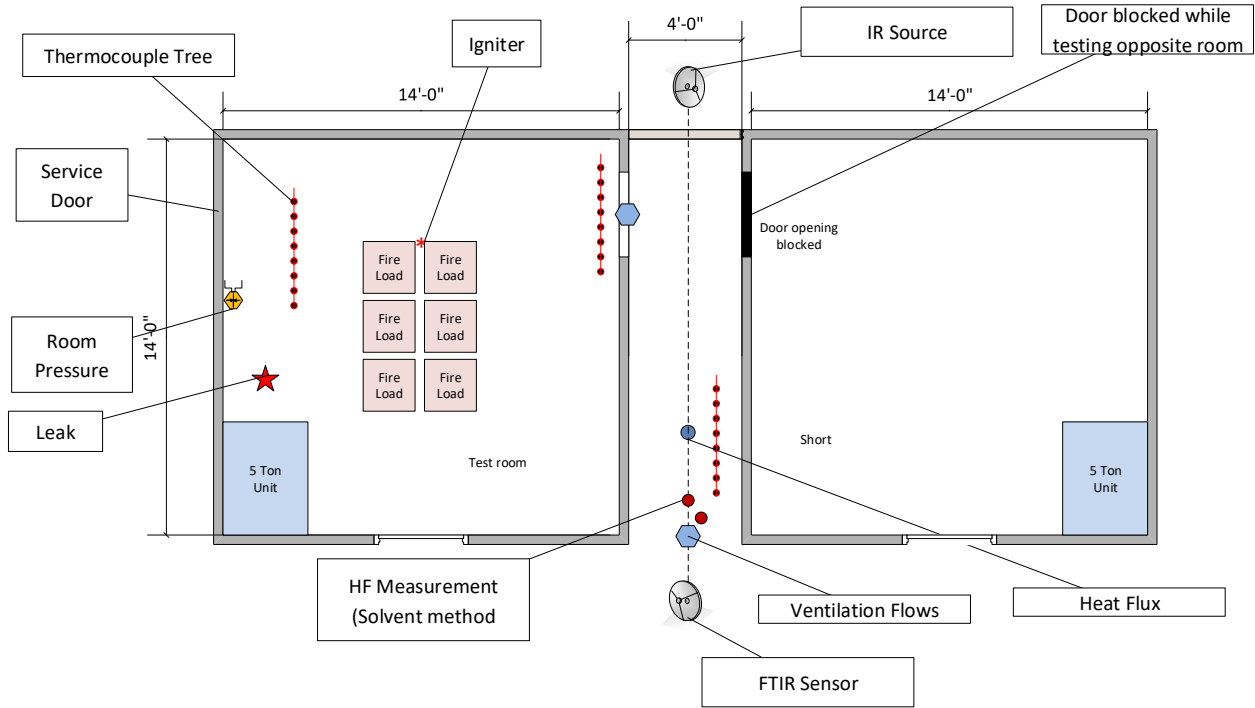


Figure 30 – Two room structure for Scenarios 2, 4, and 5

Figure 31 shows a photo of the completed structure, showing its location under the exhaust hood.



Figure 31 – Two room structure seen from the 2nd floor observation window

The instrumentation for the tests included the following:

- Three thermocouple trees made from 18-gauge type K wire with bare beads. One tree was in the test room; the second one was placed at the doorway connecting to the hallway; and the third TC tree was in the hallway. These locations are shown in Figure 30. The TCs were located at 8, 20, 32, 44, 56, 68, 80, and 92 in. above the floor.
- Ventilation flows are measured at 5 vertical locations in the room door and hallway exit. The velocity at each of the five locations was measured using a bi-directional probe connected to a pressure transducer and a co-located thermocouple. The bi-directional probes were placed at 6, 24, 42, 60, and 78 in. above the floor in the center of the door and at the entrance of the hallway.
- An Open Path FTIR instrument. The instrument was first positioned along the centerline of the hallway at 78 in. above the floor and later at 48 in. height. During testing, the IR beam was blocked by the heavy smoke layer which prevented the collection of concentration data.
- Heat flux gauges with a range of 0-50 kW/m² were placed at the hallway entrance at elevations of 2, 3, and 4 feet with the face of the gauge point horizontally down the hallway.
- Two acid gas probes, each with seven holes over a length of 30 in. were placed in the hallway entrance. The top probe covered the range of 54 to 84 in. above the floor while the bottom probe sampled the range from 24 to 54 in. above the floor.

Figure 32 shows the location of various instruments at the hallway entrance. The bidirectional probes in the compartment doorway can be seen in the background.

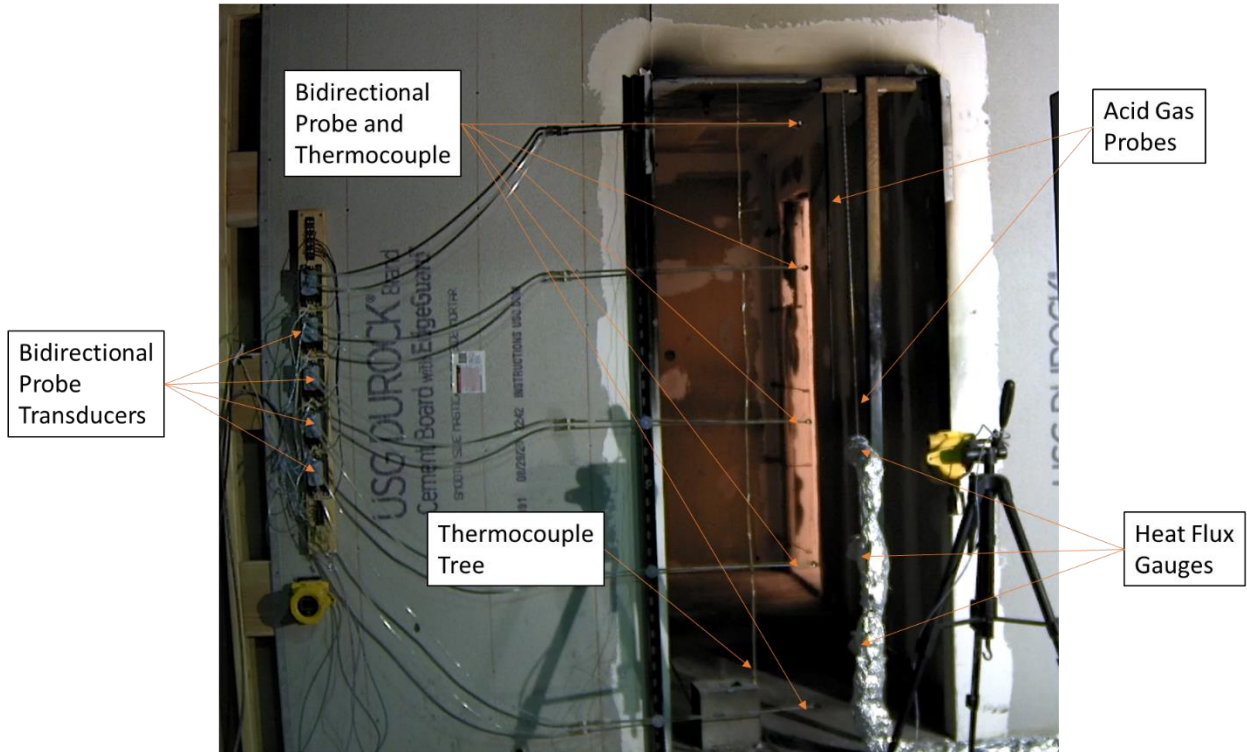


Figure 32 – Instrument locations at the hallway entrance

The HVAC unit was instrumented to monitor temperature within the unit at several locations near the refrigerant coil (A-coil). These locations are shown in Figure 33. The sheet metal enclosure cover was re-installed for the tests.

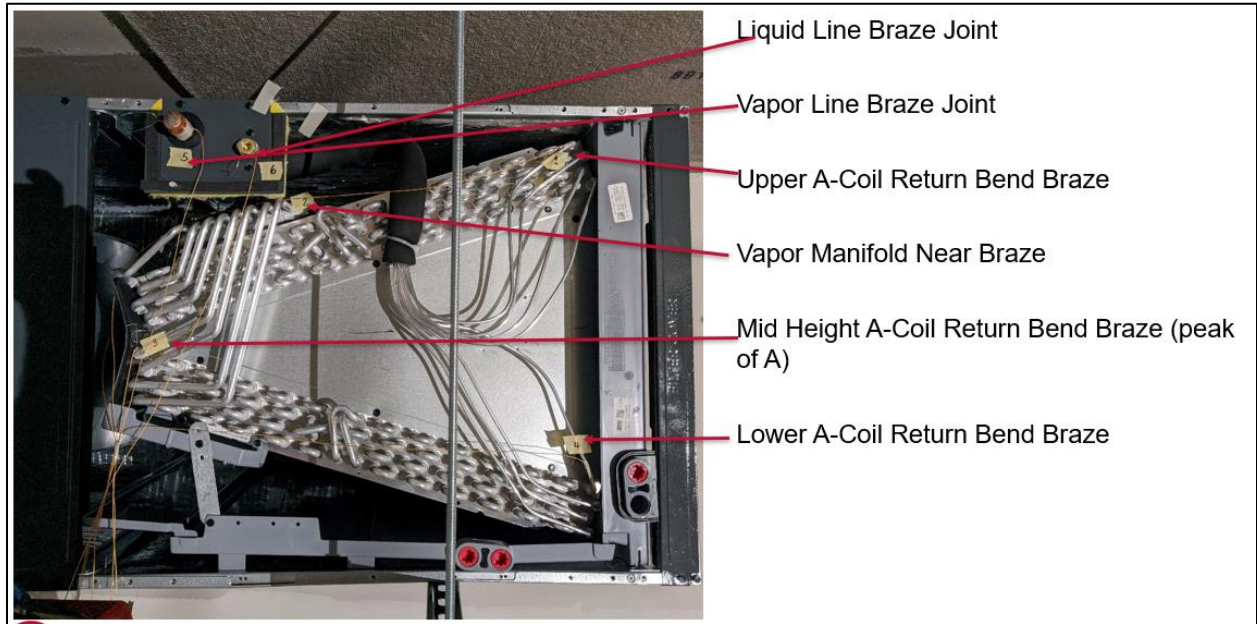


Figure 33 – Additional thermocouples added to the air handler

9.2.4. Fuel Load

The design of the fuel package used in Scenario 2 was intended to result in a ventilation limited condition in the room. The fuel package consisted of a stack of 2 wide x 3 long x 3 tall (18 total) Group A plastic commodity classification boxes (UL 199, Standard For Safety For Automatic Sprinklers for Fire-Protection Service). A cutaway view of one box is shown in Figure 34.



Figure 34 - Group A Plastic Commodity (partially cut box to show the cup arrangement)

To verify that ventilation conditions were established, a fire test was conducted under the calorimeter without any confining walls to limit the flow of air to the fire. Figure 35 shows the arrangement of boxes

as they were placed under the calorimeter hood. The photos are at the time of ignition and 5 minutes (300 s) post-ignition.

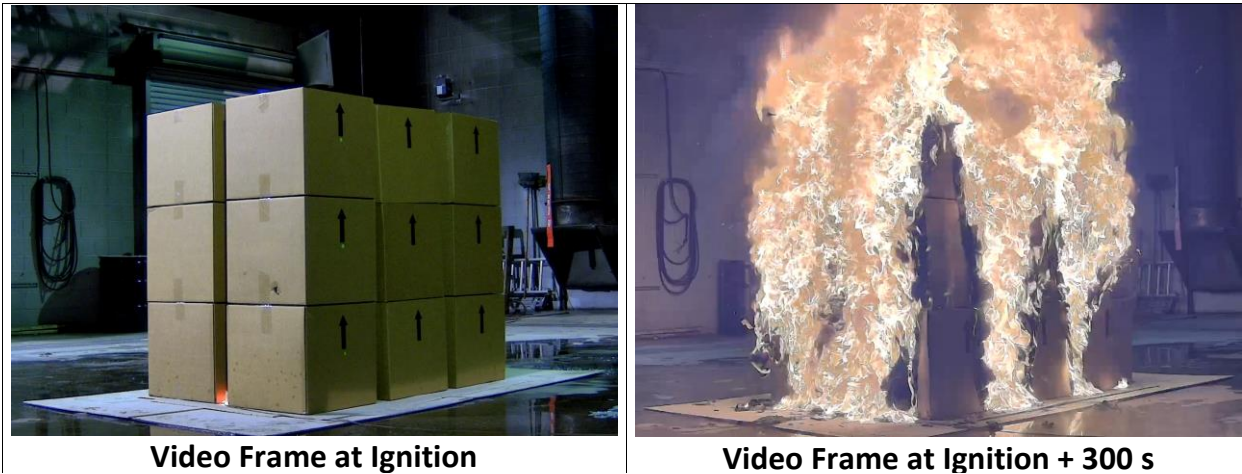


Figure 35 – Fire Load at Ignition and 5 minutes later

Figure 36 shows the measured heat release rate during the free burn of 18 boxes. The term free burn means that there was no restriction of fresh air flow to the fire. The entire plume from the fire was captured and exhausted from the calorimeter up until the 5,000 kW mark when the plume was large enough to exceed the exhaust capacity of the calorimeter. The peak HRR was 6,500 kW. Note that during the compartment fires, ventilation-controlled conditions (oxygen limited) resulted in a much lower HRR of 2,300 kW.

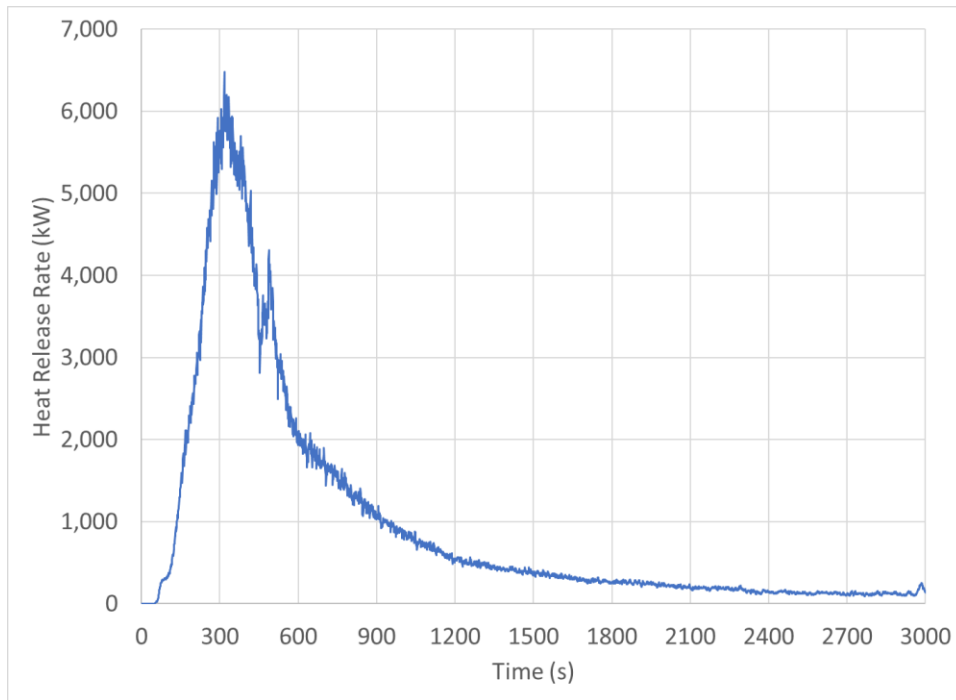


Figure 36 – Heat Release Rate: Free Burn of 18 boxes

Peak heat release rates in Scenario 2 tests were below that of the free burn as shown in Table 10. This indicates that the fire size was ventilation limited.

9.2.5. Test Procedure

The test procedure in this scenario consisted of the following generalized steps:

- Verify that the Calorimeter exhaust hood is operating
- Check that all instruments and data acquisition system are operating
- Refrigerant release tank filled and heated to the correct pressure
- Video cameras positioned as needed including view of marquee showing test parameters
- Fire load in place and igniter prepared.
- Take baseline data for 5 minutes
- Ignite the fire using the electric match and allow the fire to develop for 6 minutes
- Start the refrigerant discharge and continue for 3 minutes
- Allow the fire to continue for an additional 2 minutes and initiate test room sprinkler.
- Qualified individuals in turnout gear finally extinguish the fire using a hand line,
- Monitor acid gas conditions for safe concentrations prior to entering the lab
- Collect bubbler liquid samples and label for post-test analysis

A full description of the Scenario 2 test procedure is contained in Appendix B.

9.2.6. Scenario 2 Results

Since the fires were all similar in growth and size, Table 8 captures a series of images from different cameras beginning at ignition and ending with the start of suppression. The photographs in Table 8 are from S2-03 (R-32 Outside release) and are typical of the entire test series. The refrigerant release (from time 11 to 14 minutes) did not visibly change smoke conditions in the hallway. The largest single source of increase in smoke in the hallway occurred when the sprinkler head was activated.

Table 8 – Typical Ignition and Fire Growth









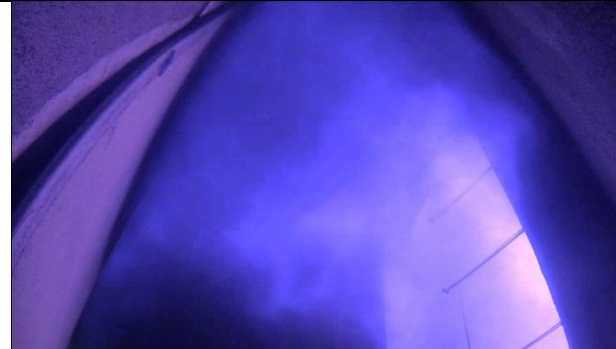



	
<p>Ignition</p>	<p>Ignition + 1 minute</p>
	
<p>Ignition + 2 minutes Smoke layer at top of boxes (50-60 in.)</p>	<p>Ignition + 2 minutes (Hallway camera) Smoke and ash carried into hallway</p>
	
<p>Ignition + 6 minutes (hallway camera) Discharge started</p>	<p>Ignition + 6 minutes (hallway Entrance) Discharge started</p>

Table 9 – Typical Ignition and Fire Growth (2)

	
<p>Ignition + 6 minutes and 30 seconds Hallway camera</p>	<p>Ignition + 6 minutes and 30 seconds Hallway Entrance</p>
	
<p>Ignition + 9 minutes Discharge Stopped</p>	<p>Ignition + 9 minutes Discharge Stopped</p>
	
<p>Ignition + 11 minutes Sprinkler head Activated Smoke pushed to floor level</p>	<p>Ignition + 11 minutes Sprinkler head Activated</p>
<p>Ignition + 19 minutes Extinguished by handline</p>	

Heat release rate results

The peak heat release rates in each test are shown in Table 10. At this HRR level the measurement uncertainty of the calorimeter is ±11% of reading or approximately ±220 kW (k=1). The standard error of the mean for the average column is $\frac{220kW}{\sqrt{180}} = 16 kW$ (k=1). It appears that HRR for the outside releases was significantly lower when compared to the baseline, while the inside release of R-32 showed a similar HRR as the baseline. Releases were made either outside or inside the air handler. The outside release simulated a line break going into the unit while the inside release simulated a failure in the A-coil.

Table 10 – Scenario 2 Peak Heat Release Rates

Test#	Refrigerant	Leak (lbm)	Refrigerant Release Location	HRR (kW) During Release	
				Peak ±k=1	Average ±k=1
S2-01	Baseline	None	No refrigerant	2360 ±220*	2109 ±16**
S2-02	R-410A	20	Outside	2530 ±220	1970 ±16
S2-03	R-32	16	Outside	2290 ±220	1915 ±16
S2-04	R-32	16	Inside	2460 ±220	2088 ±16

* – Measured peak prior to 900 s, test time, 2730 kW during extended burning time

** – Average during the 180 seconds of discharge

The charge amount for R-32 is lower than R-410A due to the properties of the refrigerants needed to support a 5-tonR unit with a long lineset. R-466A was not tested in this scenario due to the permitting issues with stack effluents of iodine.



Figure 37 shows the chart of heat release rates for each of the four Scenario 2 tests. The baseline test continued longer than the other three tests. This was done to determine the refrigerant release time and post-release duration before suppression. The fire was suppressed to prevent fire damage to the test structure. In the three release cases, HRR during the release was lower than the baseline fire. At this level of heat release rate, the calorimeter has a measurement uncertainty of $\pm 11\%$ ($k=1$) of measured value or ± 220 kW. Scenarios S2-01 and S2-03 used the left-side room shown in Figure 30, while S2-02 and S2-04 used the right-side room.

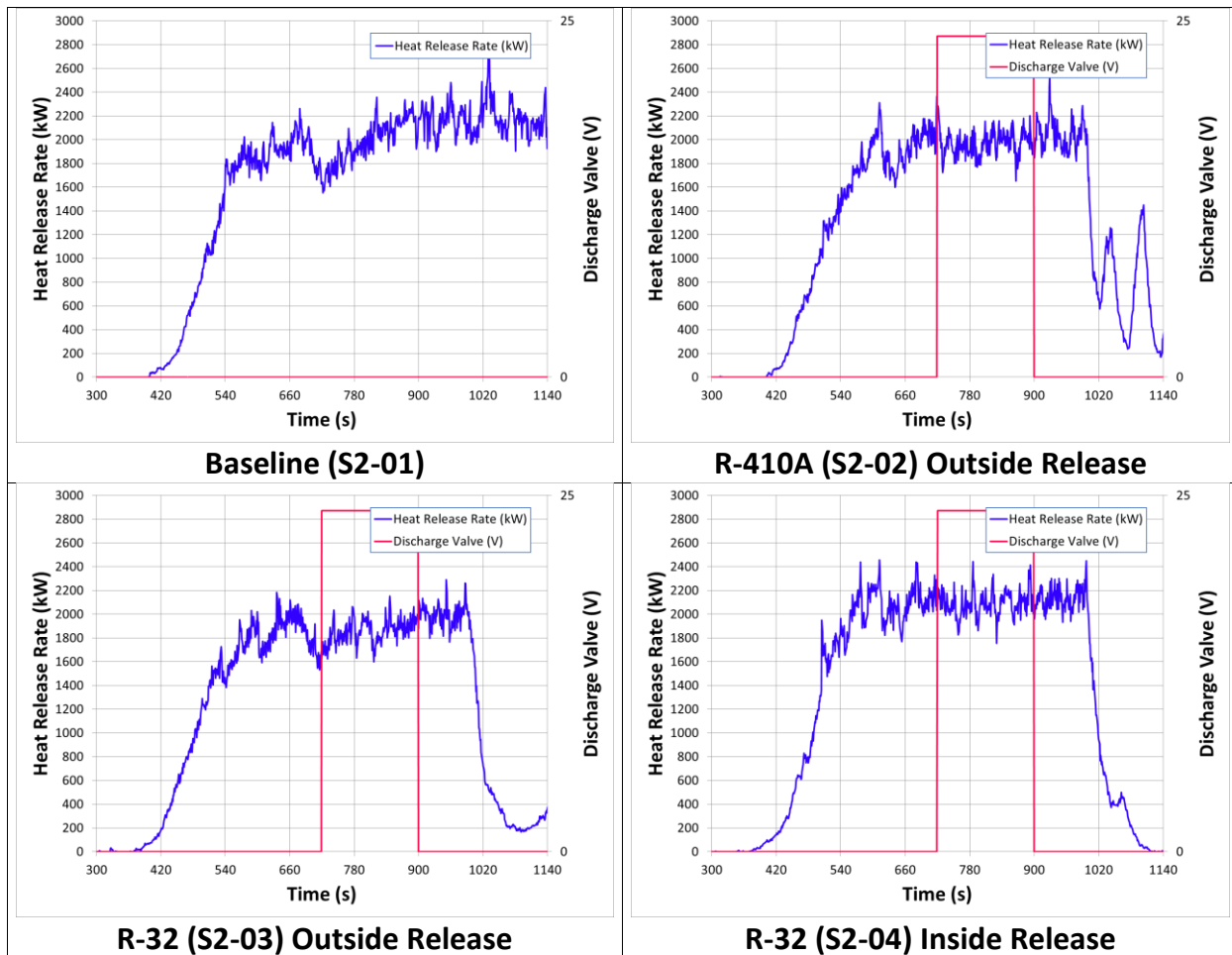


Figure 37 – Scenario 2 Heat Release Rates

Heat flux results

Heat flux was measured at the hallway entrance at 2, 3, and 4 feet above the floor to simulate the heat flux exposure to firefighters in a crouched position getting ready to attack the fire. Figure 38 shows the measured heat flux in each of the four tests. The baseline test data is anomalous due to problems with the instrumentation and cooling systems and cannot be compared to the other three tests where these problems were resolved.

Other than the noise caused by the turbulent hot gas layer, the heat flux levels at the 4-foot level average out to about 7 – 9 kW/m² during the fire. The flareup in the R-410A (S2-02) was due to initiation of sprinkler suppression and the resulting push of flame down the hallway.

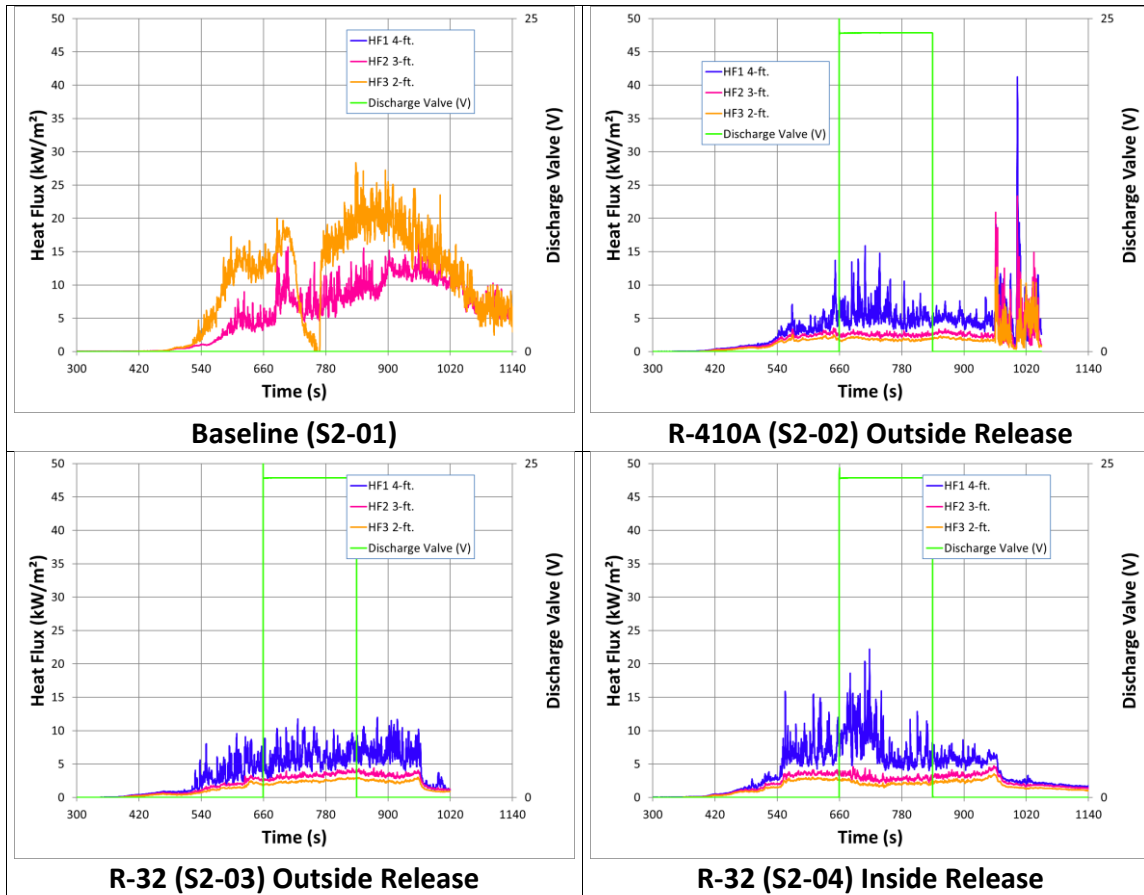


Figure 38 – Scenario 2 Heat Flux Measurements

Temperature Results

The following figures show the temperatures measured at the four locations. Table 11 records the peak temperatures at the various locations.

Table 11 – Scenario 2 Peak Temperatures.

Test#	Refrigerant	Leak (lbm)	Leak Location	Peak Room Center (°C)	Peak Door (°C)	Peak Hallway Entrance (°C)	Peak Air Handler (°C)
S2-01	Baseline	None		860	860	840	780
S2-02	R-410A	20	Outside	900	900	740	910
S2-03	R-32	16	Outside	1180	900	680	750
S2-04	R-32	16	Inside	870	910	710	950

Hallway Entrance Temperatures

Figure 39 shows the temperatures at the hallway entrance. These temperatures were lower than those observed in the room and hallway door. This is due to some mixing with the incoming air at the floor level. The figure shows that temperatures at the 8 in. and 20 in. level were only slightly above ambient temperature due to the inflow of ambient air. At the 32 in. level and above the temperatures are significantly higher due to the outflow of hot gases through the hallway.

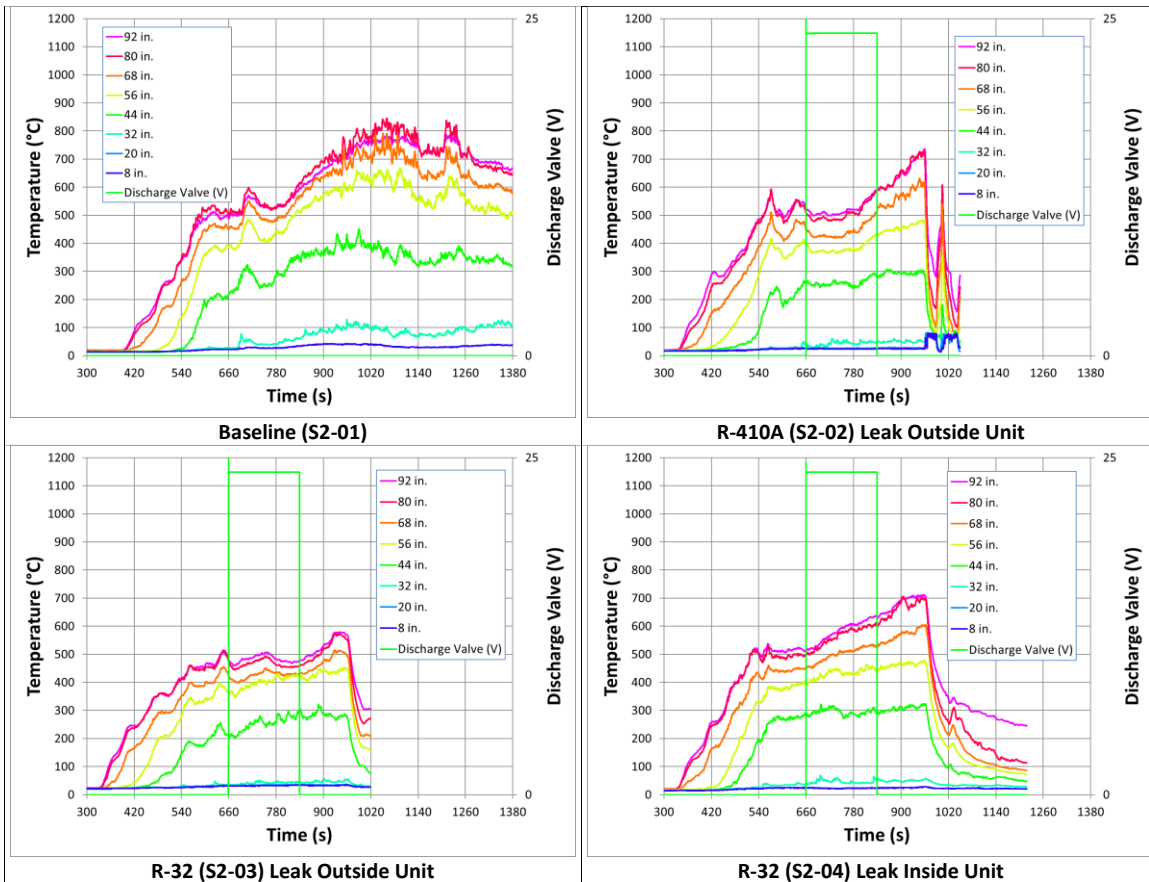


Figure 39 – Scenario 2 Hallway entrance temperatures

Hallway Door Temperatures

Figure 40 shows the temperatures at the doorway from the room into the hallway. The baseline test shows nearly uniform temperatures from floor to ceiling at the 900 s point. This is a characteristic of a ventilation limited fire where convective and radiative heat transfer mechanisms cause these uniform temperatures. This behavior was not observed in the tests with leaks outside of the air handler indicating that the release limited the ability of these two mechanisms. The inside leak (R-32, S2-04) is similar to the baseline test.

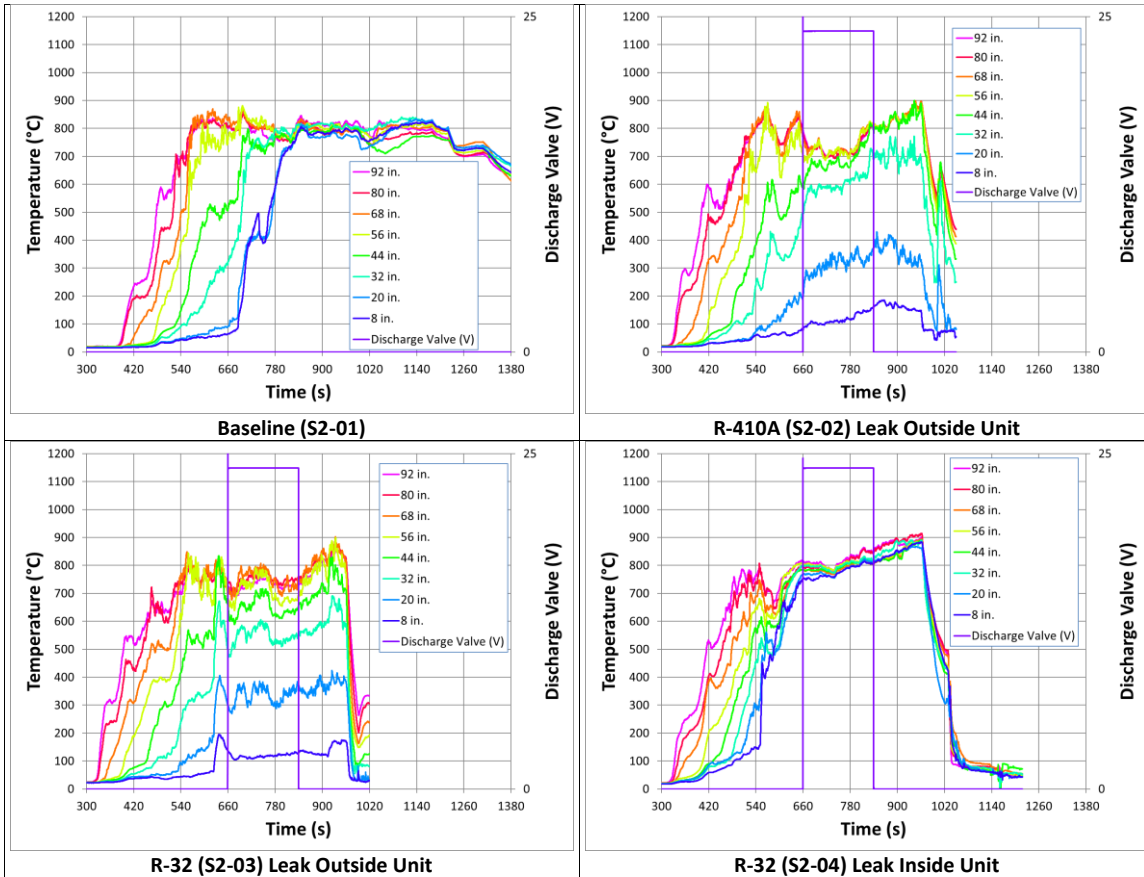


Figure 40 – Scenario 2 Door Temperatures

Room Temperatures

Figure 41 shows the temperatures in the room (see Figure 30 for location). The time axis begins at 5 minutes (300 s) after the beginning of the test. This period of time was used to allow the room to settle prior to ignition of the boxes. The refrigerant release was planned for 3 minutes (180 s) and was consistently started 11 minutes (660 s) after the test start. The figures show a flattening of the temperatures during the period of release the R-410A and the R-32 (inside unit) while the baseline and the R-32 (outside unit) show continuing increases during the same time period. The thermocouples were arranged in a vertical “tree”, with bare beads exposed every 12 in. beginning at 8 in. above the floor.

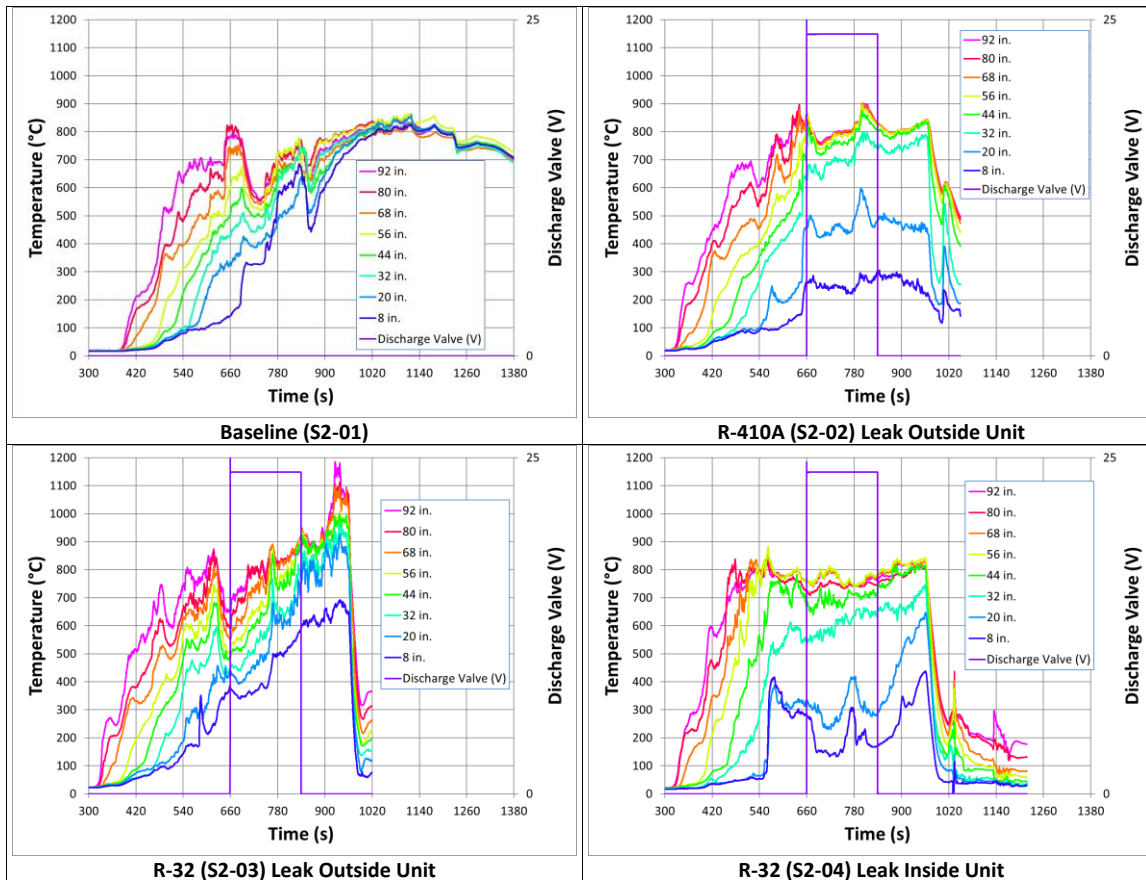


Figure 41 – Scenario 2 Temperatures in the room

Air Handler Temperatures

Figure 42 shows the temperatures recorded at the air handler (locations shown in Figure 33). These temperatures are slower to rise than the thermocouples in the room due to the insulating effect of the air handler enclosure. The melting point of aluminum is 660°C and these thermocouples were in direct contact with the aluminum components of the A-coil. Most of these thermocouples stabilized 50 to 100°C above this melting point. The exception to this is the R-410A test where temperatures spiked to 800-900°C following completion of the discharge.

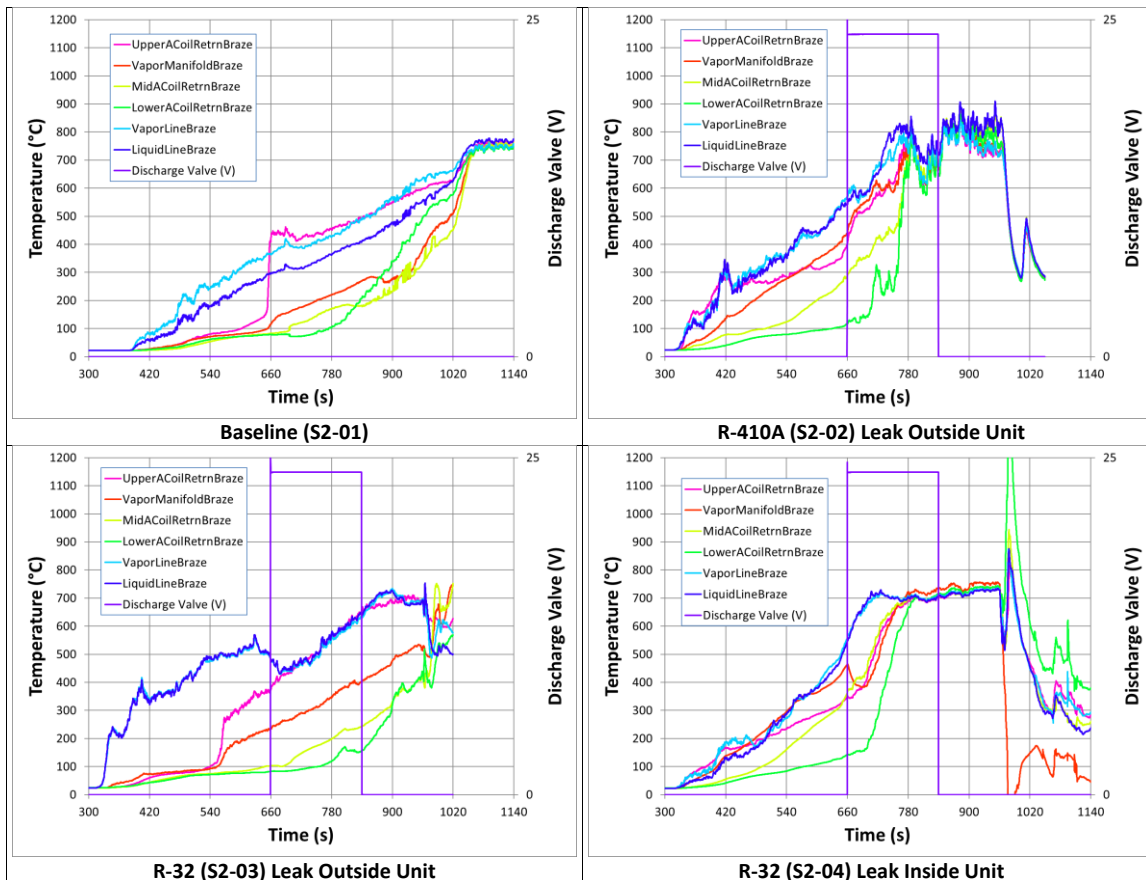


Figure 42 – Scenario 2 temperatures at the air handler

HF concentration by Open Path FTIR

The open path FTIR instrument’s beam was blocked by the heavy smoke layer. No data was generated from this instrument.

Hydrogen Fluoride Using Aqueous Solution

The locations of the acid gas sampling probes are shown in Figure 32. Each bubbler was filled with 50 ml of distilled water. The flow through each probe was set to a constant 0.5 L/min. The sample was collected throughout the time of the discharge, 3 minutes. After the test the liquid samples were collected according to procedure and analyzed.

Table 12 compares the R-410A and R-32 results of the calculated average concentration of fluoride ions for the outside releases. The highest concentrations were measured high in the hallway.

Table 12 – Scenario 2 HF concentrations in air (Releases outside the air handler)

Test	Refrigerant	Leak Location	Hallway Sample Location	Average Fluoride Concentration in Air (ppm v/v)*
S2-02	R-410A	Outside	Low	10
			High	37
S2-03	R-32	Outside	Low	5
			High	19

* -- The measurement uncertainty of these concentrations was ±20% (k=1) excluding the amount HF loss in the collection hood and concentrations remaining in the sample tubing. This additional uncertainty could not be quantified. See section 7.5.2 for discussion.



Table 13 compares the outside and inside releases of R-32. The releases inside the unit showed significantly higher concentrations than the release outside the unit. The outside release showed higher concentration at the low sample probe in the hallway indicating some change in the dynamics for a release from the A-coil as compared to a release outside the unit and located higher in the room. A release test of R-410A inside the unit was not performed because this observed difference in dynamics was not observed until after the bubbler samples were analyzed and the test facility was no longer available. At the time of Scenario 2 testing, the best information available showed that an inside release of R-410A would be similar to the release of R-32.

Table 13 – Scenario 2 HF concentrations comparing R-32 releases inside and outside the air handler

Test	Refrigerant	Leak Location	Hallway Sample Location	Average Fluoride Concentration in Air (ppm v/v)*
S2-03	R-32	Outside	Low	5
			High	19
S2-04	R-32	Inside	Low	427
			High	230

* -- The measurement uncertainty of these concentrations was $\pm 20\%$ (k=1) excluding the amount HF loss in the collection hood and concentrations remaining in the sample tubing. This additional uncertainty could not be quantified. See section 7.5.2 for discussion.

Post-test Photos

Photos of the air handler after each test showed significant damage and clear observation of melted aluminum components. Figure 43 shows a typical A-coil before and after testing. There is much evidence of missing or melted aluminum components (return bends, feeder tubes and the suction tube copper to aluminum interface joint). The coil had no refrigerant in it as previously planned for Scenario 3.

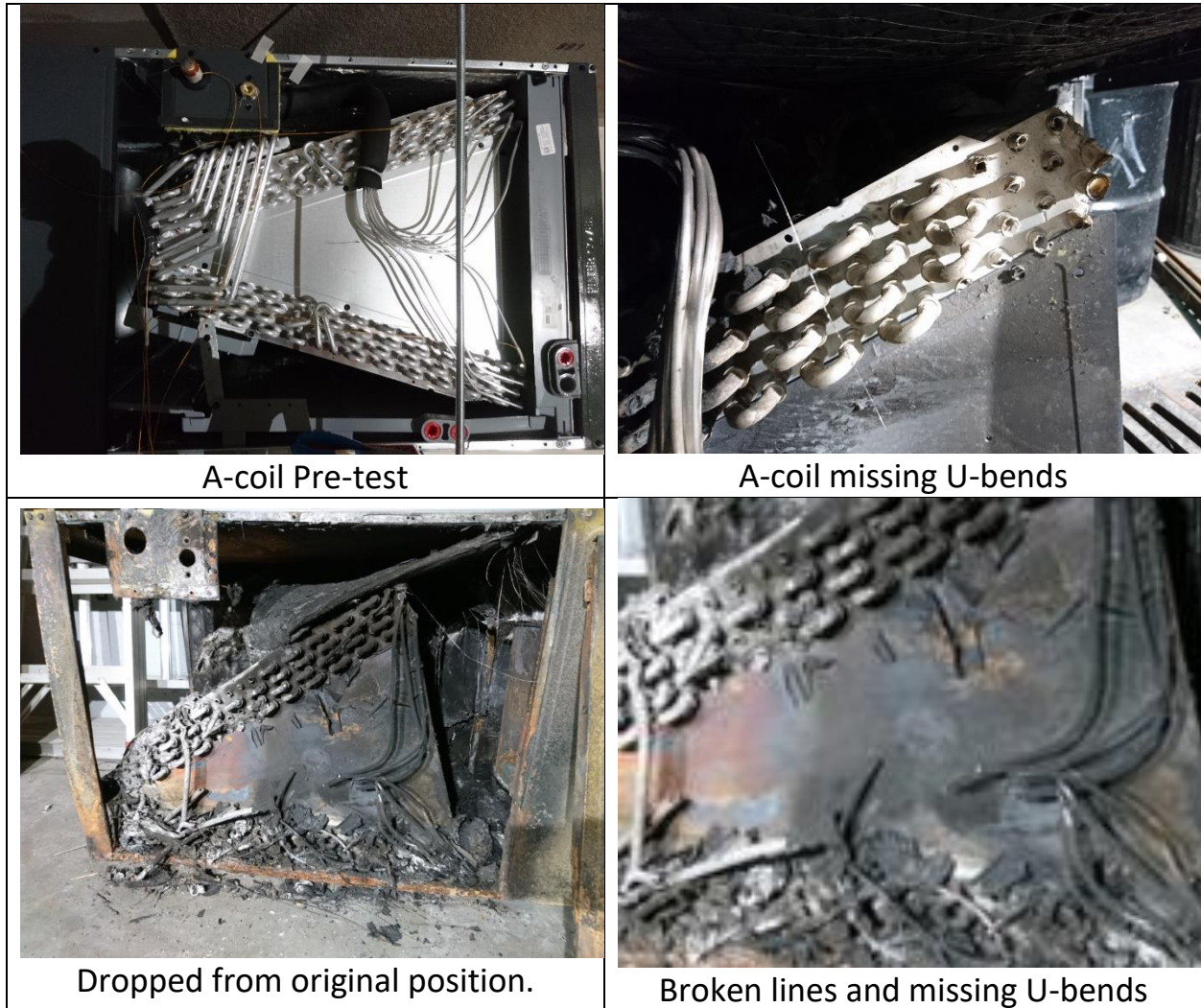


Figure 43 – Scenario 2 A-coil typical damage

Figure 44 compares the room before and after testing. While difficult to see in the right side photo, then heat was intense enough and long enough in duration to cause the uni-strut members supporting the air handler to deform. The photo also shows that most of the fire load has been consumed. There is a small remnant of melted plastic and cardboard.

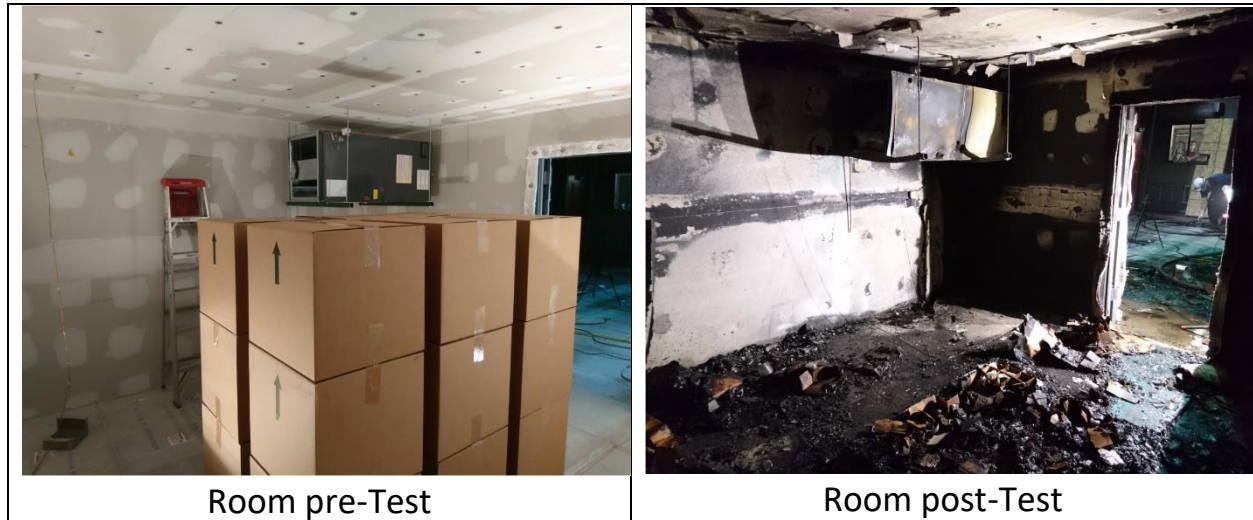


Figure 44 – Scenario 2 room: Pre- and Post-Test

9.2.7. Scenario 2 Summary

A summary of the results from Scenario 2 are as follows:

- The compartment fires were ventilation limited when compared to the free burn of the same fuel load. The compartment fires peaked in the range of 2,300-2,500 kW, while the free burn peaked at 6,500 kW.
- There were no significant differences in the heat release rates (comparing baseline to refrigerant release tests) as the differences were within the measurement uncertainty at this level of HRR.
- There was no significant difference in heat flux in the hallway when comparing the release tests with the baseline test without any refrigerant released.
- Temperatures at the floor level in the hallway entrance remained at ambient conditions due to the influx of air caused by ventilation limited conditions.
- Temperatures at the air handler were sufficient to melt aluminum which would have resulted in a catastrophic leak, so it was concluded that test 3 need not be run
- Hydrogen fluoride measurements by the bubbler method for the outside release were about the same when comparing R-410A to R-32. The measurements for the R-32 inside release were 5 to 40 times larger than either of the two outside release tests.
- A test was not conducted with R-466A because the design of the smoke abatement system was unable to prevent stack releases of iodine.
- A test with R-454B refrigerant was not performed since the baseline test and tests with R-410A and R-32 showed little difference in heat release rates.

9.2.8. Firefighter Tactical Considerations for A2L Refrigerants Scenario 2

Hazard	Result	Comment
Heat Release Rate (HRR)	<p>HRR from the fuel package used resulted in a ventilation-limited fire between 1900 and 2300 kW</p> <p>HRR was similar in comparing the baseline fire to those with refrigerants.</p>	<p>Releases of A1 and A2L did not measurably increase the HRR.</p> <p>A fire of this size is comparable to a well-ventilated fire in an easy chair. Refer to Appendix H for more information.</p>
Heat Flux Hallway Entrance	<p>Heat flux levels at the 4 ft. level were observed to be in the range of 5 to 10 kW/m² just prior to the refrigerant release (6 minutes after ignition). During the refrigerant release heat flux was observed to increase by average of about 3 to 4 kW/m².</p>	<p>Heat flux at the 2 and 3 ft. levels at the hallway entrance were in the range of 2-4 kW/m².</p> <p>Firefighters may work safely for a short period of time at elevated heat flux levels. The maximum time of exposure for heat flux at 2 kW/m² is 15 minutes. The maximum time of exposure for heat flux at 10 kW/m² is 5 minutes [5], [6]. Refer to Appendix H for more information.</p>
Temperature Hallway Entrance	<p>Temperatures at 8 through the 32 in. level in the hallway ranged between ambient temperatures and 50°C due to incoming air inflow.</p> <p>Temperatures at and above the 44 in. level ranged from 300°C to as much as 800°C at the 80 in. level (570°F to 1450°F).</p>	<p>Temperatures at the 44 in. level either increased or remained the same during the refrigerant release and were greater than 250°C (480°F)</p> <p>The coolest temperatures were observed at the 32 in. level and below due to incoming air. Maximum temperatures at that level were 50°C (122°F).</p>
Deflagration	<p>No deflagration was observed.</p>	<p>Smoke levels and velocities in the hallway did not change during the refrigerant release.</p>
Hydrogen Fluoride (HF) generation	<p>All scenario 2 fires with refrigerant release showed measurable HF concentrations at the mid- and higher locations at the hallway entrance.</p>	<p>HF and other halogen compounds are inhalation and skin contact hazards. Contact with contaminated turnout gear can lead to exposures if not properly cleaned.</p> <p>Fire service personnel need to don appropriate PPE for all phases of operation from suppression, to overhaul, investigation, and recovery.</p> <p>Refer to Appendix G for a further discussion of hazards from fluorine compounds.</p>



9.3. Scenario 3

This scenario was planned as optional pending a review of Scenario 2. The difference between Scenario 2 and Scenario 3 is that the leak would not be forced as in Scenario 2. Instead, a fully charged 5-ton unit including the outdoor unit and lineset would be exposed to the fire conditions. In Scenario 2, leakage was forced at the location of the brazed joint outside the HVAC unit. The data showed the room contents fire developed temperatures high enough to cause the brazed joints at the unit to fail. Post-test observations of the HVAC unit also revealed that system components had melted during the test. Two more tests were added in Scenario 2 with leakage forced within the HVAC unit to investigate if this may create more hazardous fire exposure conditions for the firefighters if they were advancing from the corridor (i.e., temperature, heat flux) to the room of fire origin. Since the forced leak, either inside or outside the unit did not create more hazardous conditions in the corridor area, it was concluded by onsite UL staff, AHRI and fire service observers that a similar failure would occur in Scenario 3 and no new information would be developed by performing Scenario 3 tests.

9.4. Scenario 4

The objective of Scenario 4 was to assess the hazards in fire room during overhaul activity if firefighters' actions result in a catastrophic refrigerant line break.

The results from Scenario 1 were used to inform modifications to Scenario 4 test setup in the UL proposal to increase the dwell time of the refrigerant discharge in the proximity of a fire source. It was anticipated that this would facilitate interaction with the fire. These modifications were discussed with and approved by AHRI PMS and FSRI.

9.4.1. Test Setup

The tests were performed in one of the 14 x 14 x 8-ft. high rooms.

Figure 45 shows the arrangement of the room and the equipment.

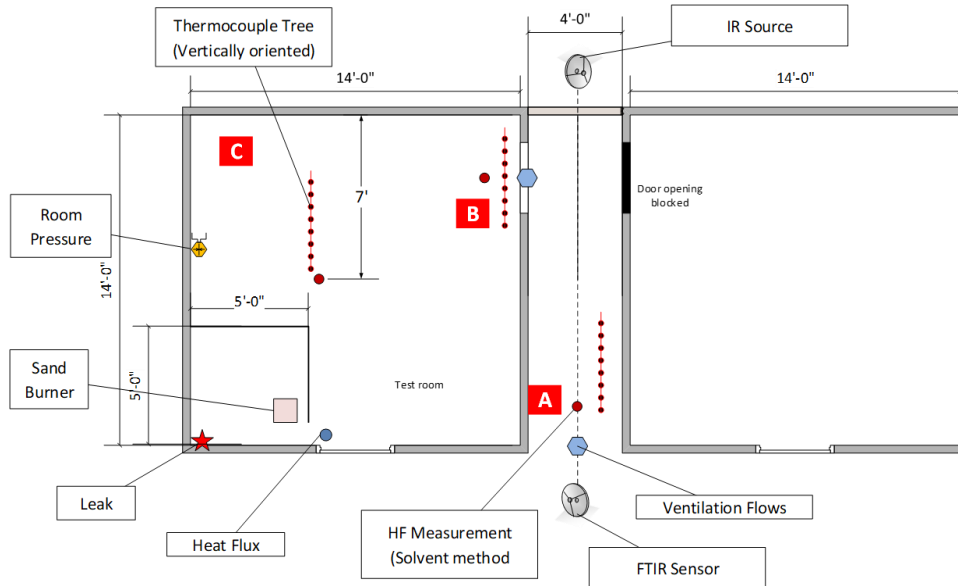


Figure 45 – Scenario 4 Room and Equipment

A 5 x 5 x 3-ft. (L x W x H) enclosure was built inside the room. There was a 1-foot wide gap near the sand burner. The refrigerant discharge orifice was mounted 4 feet above the floor and 1 foot from the side wall. The flow was directed downward so that it impacted the 3-ft wall before circulating within that space toward the sand burner operating at 40 kW. Figure 46 shows photos of the room. This design was intended to reduce the high velocity of the discharge and increase dwell time within the sand burner flame.

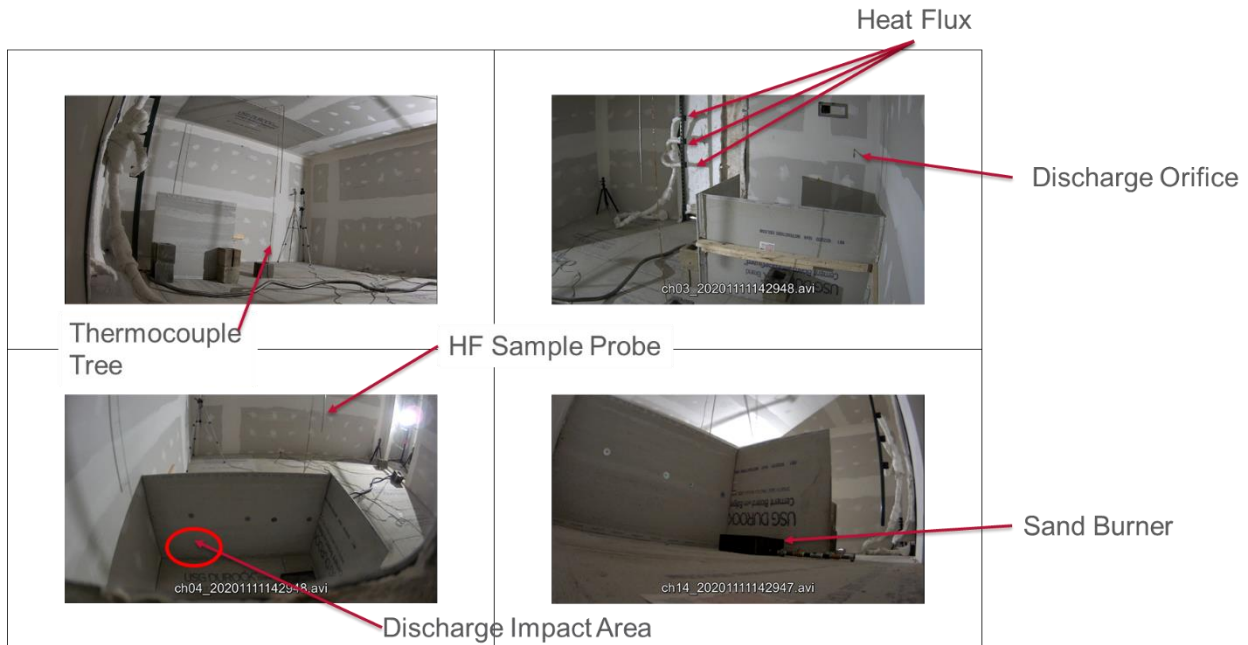


Figure 46 – Scenario 4 Photos from various angles

9.4.2. Test Procedure

The test procedure in this scenario consisted of the following generalized steps:

- Check that all instruments and data acquisition system are operating
- Refrigerant release tank filled and heated to the correct pressure
- Video cameras positioned as needed including view of marquee showing test parameters
- Start the sand burner fire and take baseline data for 5 minutes
- Start the refrigerant discharge and stop after 9 minutes
- Continue data acquisition for another 5 minutes
- Monitor acid gas conditions for safe concentrations prior to entering the lab
- Collect bubbler liquid samples and label for post-test analysis

A full description of the Scenario 4 test procedure is contained in Appendix C.

9.4.3. Results

Refrigerants R-410A, R-32, and R-454B were used in this test series. R-466A was not planned to be part of this test series.

Visual Observations

Figure 47 and Figure 48 show the flame shape (40 kW) prior to the release and the flame shape during the release, respectively. The second figure clearly shows the effect of the refrigerant discharge passing

through the flame. There was no visually obvious change in the flame size, regardless of which refrigerant was discharged.

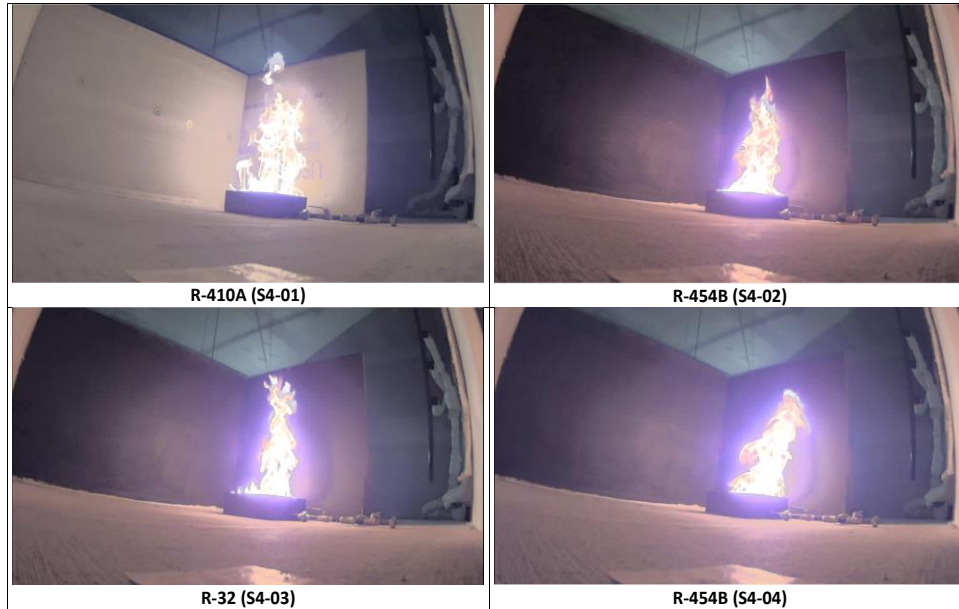


Figure 47 – Scenario 4: 40kW flame after stabilization

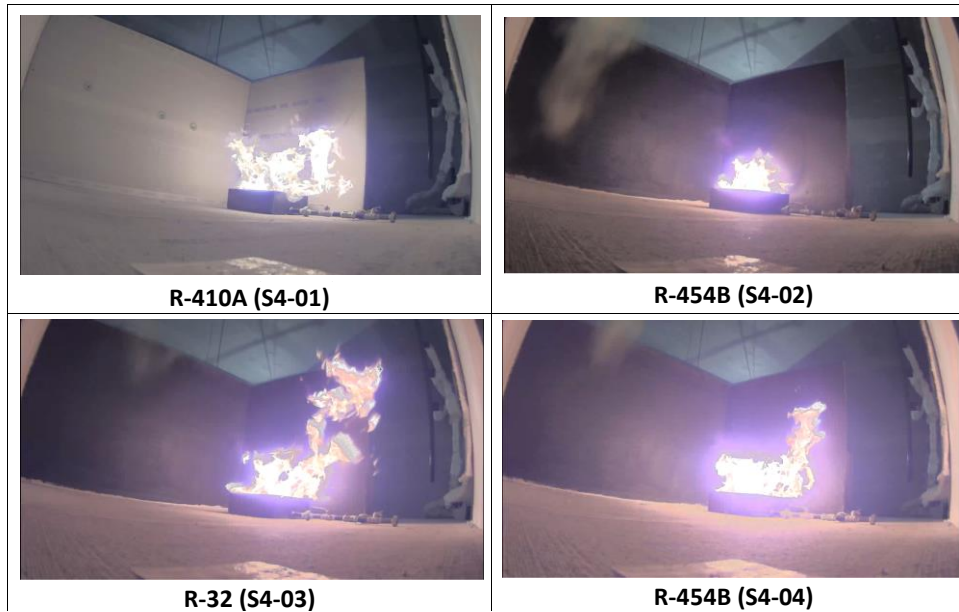


Figure 48 – Scenario 4 Flame disturbed by refrigerant discharge

Figure 48 also shows that the small enclosure walls were painted black after the first test so that the refrigerant discharge would be more visible. The mist in the upper left corner of the last three photos is the refrigerant discharge.

Heat release rate

The heat release rates for each of the four tests are shown in Table 14. The largest increase was seen in the R-410A test, but this increase may not be accurate, due to instrumentation issues and possible contamination of make-up air to the laboratory.

Table 14 – Scenario 4 Summary of Heat Release Rate

Test	Refrigerant	Tank Charge (lbm)	Average Heat Release Rate (k=1 coverage factor)		
			After warmup (kW)	During Discharge (kW)	Net Change (kW)
S4-01	R-410A	20	49 ±25	99 ±25	+50* ±36
S4-02	R-454B	17	9 ±25	26 ±25	+17 ±36
S4-03	R-32	16	26 ±25	38 ±25	+12 ±36
S4-04	R-454B	17	36 ±25	49 ±25	+13 ±36

* – Skewed due to either voltage drift, contaminated make-up air or some combination

The uncertainty of the Net Change increased due to taking the difference of two values, each with an uncertainty of 25 kW. The uncertainty of the difference is $\sqrt{25^2 + 25^2} = 36$, (rounded up).

Figure 49 shows the computed heat release rates from the calorimeter. As previously indicated, the measurement uncertainty at the low end of the calorimeter range is 62% or ±25 kW (k=1) for the 40 kW fire used in this scenario. There is anomalous data behind the plot of R-410A that skewed those results. One indication is the discharge valve voltage. This should be a constant just like in the other three tests. The variation indicates that there may have been power fluctuations during R-410A test that affected the results. There are also indications that the makeup air had been contaminated with abnormally high levels of carbon dioxide and carbon monoxide that was not present in the other three tests.

A repeat of this R-410A test at a smaller scale in the future could resolve this issue.



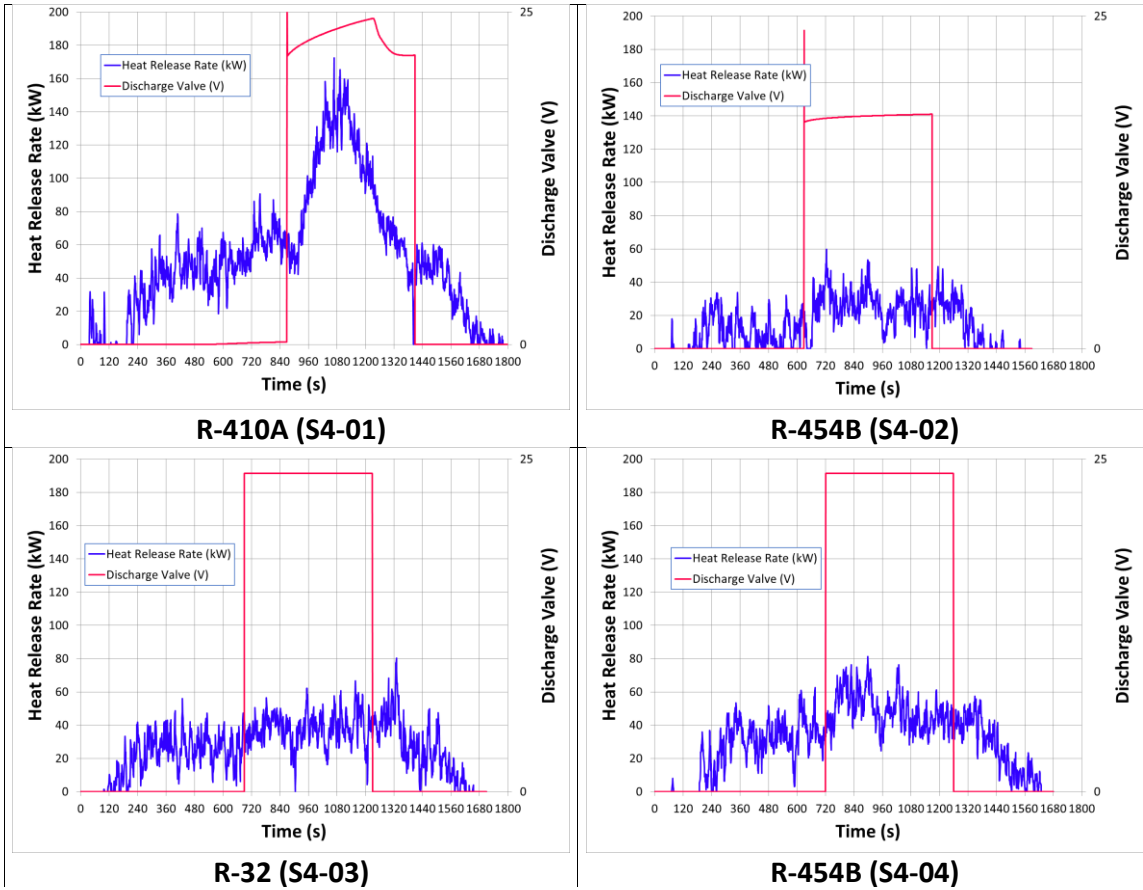


Figure 49 – Scenario 4 Heat Release Rates

Heat flux

Figure 50 shows the heat flux measured at 3, 4, and 5 feet above the floor. The increases observed are due to the sweeping effect once the refrigerant discharge begins. Prior to discharge the plume from the sand burner had been rising nearly vertically toward the ceiling. The swirling/sweeping action of the discharge pushed these hot gases toward the heat flux gauges.

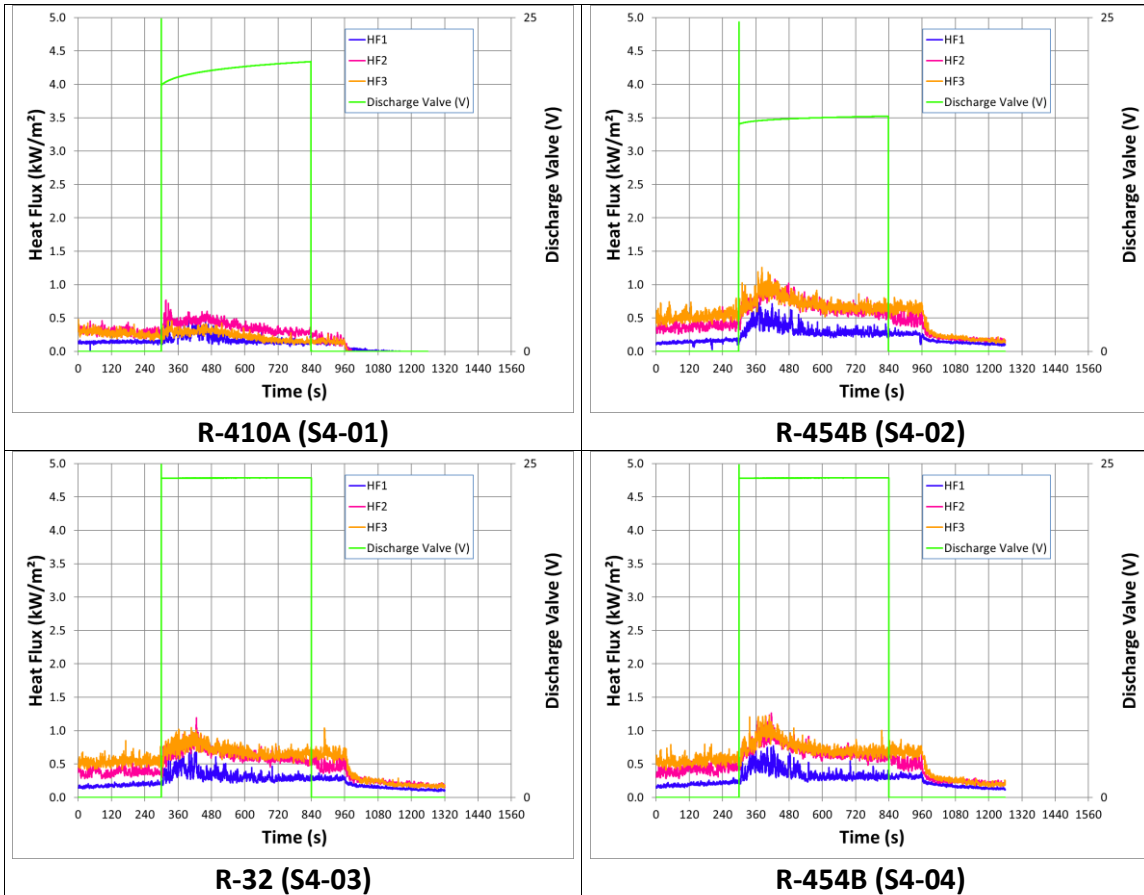


Figure 50 – Scenario 4 Heat Flux

Temperature

Figure 51 shows the temperatures at the center of the room where a firefighter might be standing. The swirling/stirring effect of the discharge is most evident at the 44 in. level. The highest temperature in the room did not exceed 90°C

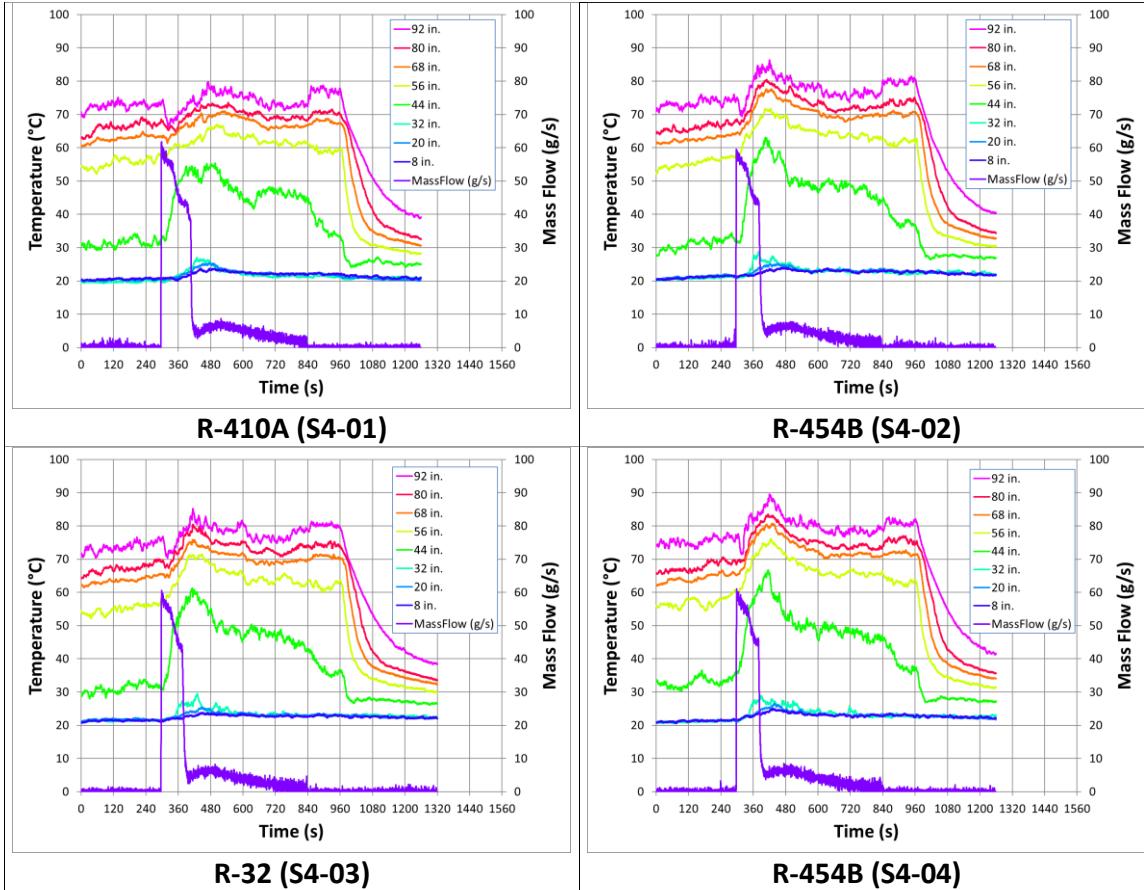


Figure 51 – Scenario 4 Room Center Temperatures

Figure 52 shows the hallway door temperatures. The effect of swirling/stirring is most visible at the 44 in. level.

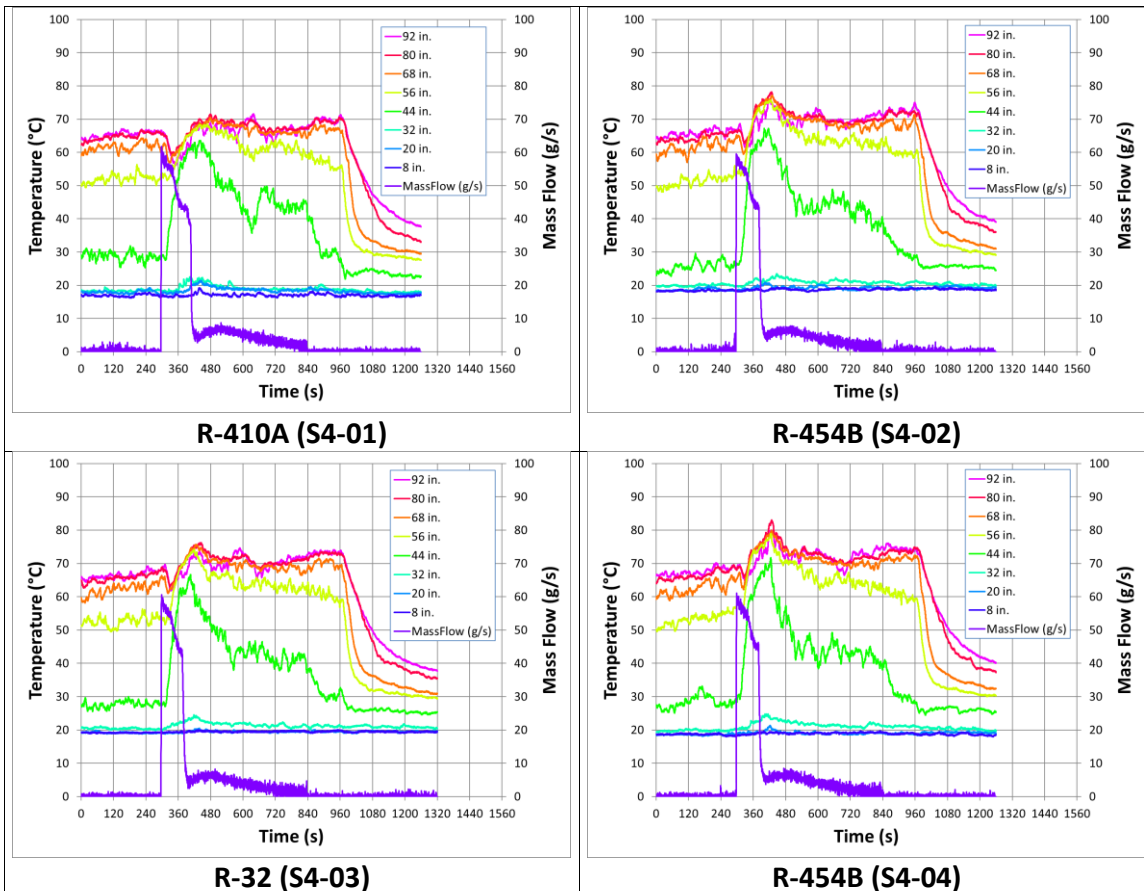


Figure 52 – Scenario 4 Hallway Door Temperatures

Figure 53 shows the hallway entrance temperatures with an overlay of the discharge flow rate for reference. The A1 refrigerant, R-410A, showed a drop (-4°) in ceiling temperatures beginning with the discharge. The A2L refrigerants showed an increase (+5°) in ceiling temperatures. These changes are relatively small, but the “hump” in ceiling temperatures between 360 and 480 seconds is unique to the A2L’s (R-32 and R-454B) but is not present in the R-410A data.

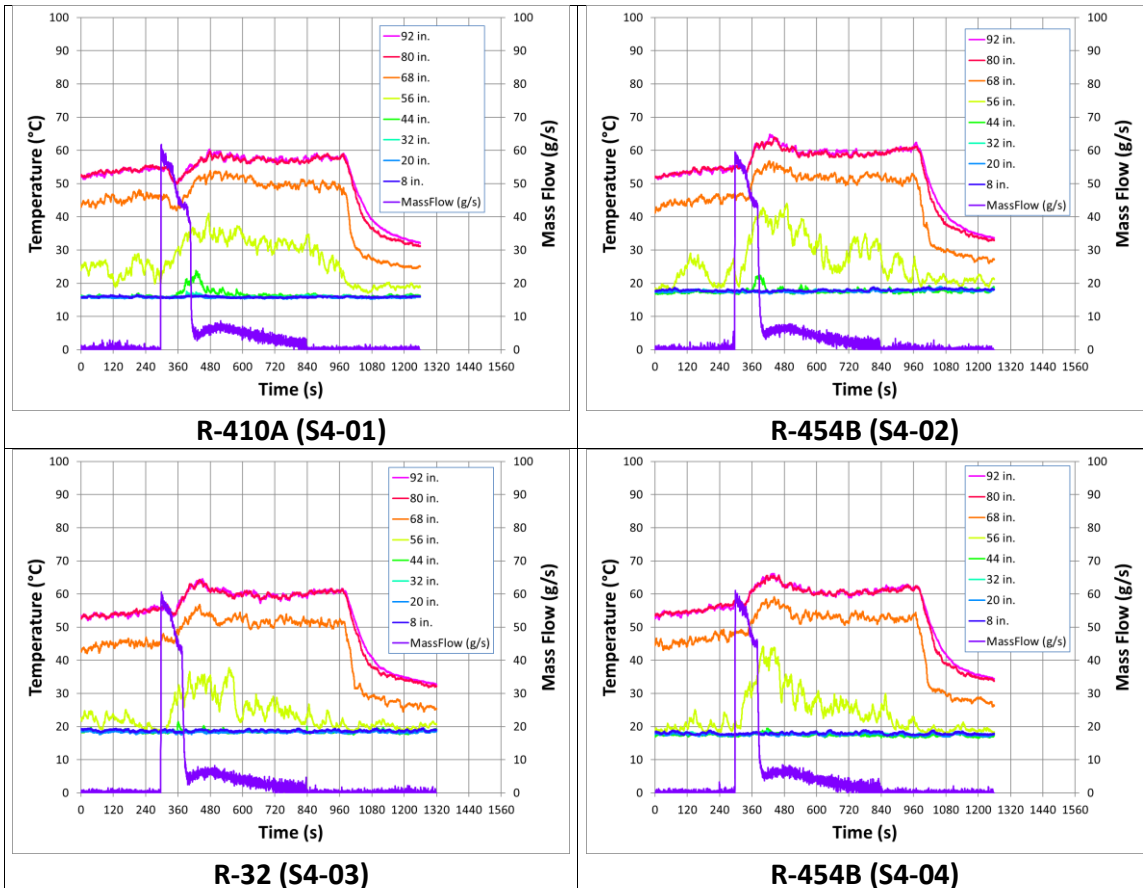


Figure 53 – Scenario 4 Hallway Entrance Temperatures

Hydrogen Fluoride Using Aqueous Solution

The solution method consisted of a sample probe at each of the locations shown in Figure 13. Each bubbler was filled with 50 ml of distilled water. The flow through each probe was set to a constant 0.5 L/min. The sample was collected throughout the time of the discharge, 9 minutes. After the test the liquid samples were collected according to procedure and analyzed.

Table 15 summarizes the average concentration of HF during the sampling period. The last three columns in the table show the ratio at each location relative to the concentration of HF from R-410A in test S4-01. Both R-454B and R-32 showed much larger relative concentrations of HF.

Table 15 – Scenario 4 HF concentrations

Test	Refrigerant	Average Concentration (ppm v/v)*			Relative to R-410A		
		Center	Door	Entrance	Center	Door	Entrance
S4-01	R-410A	70	102	92	1.00	1.00	1.00
S4-02	R-454B	126	179	151	1.79	1.74	1.64
S4-03	R-32	192	135	148	2.73	1.31	1.60
S4-04	R-454B	351	154	183	5.00	1.50	1.98

* -- The measurement uncertainty of these concentrations was ±20% (k=1) excluding the amount HF loss in the collection hood and concentrations remaining in the sample tubing. This additional uncertainty could not be quantified. See section 7.5.2 for discussion.

Figure 54 presents the same data as the table above, but as a bar chart. It appears that there may have been an increasing trend over time. This issue was discovered after all testing in the laboratory had been completed and could not be corrected. The open path FTIR also did not show a similar increasing trend.

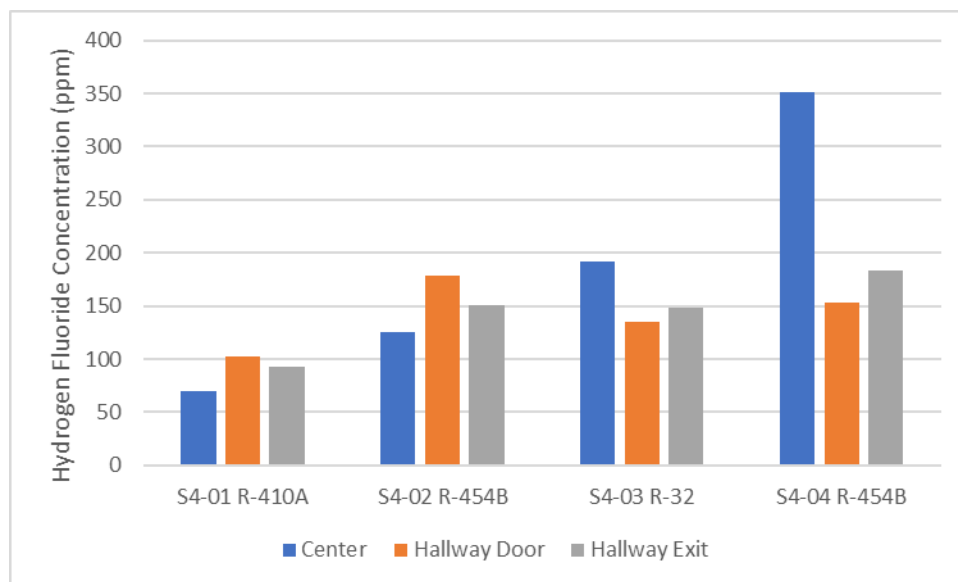


Figure 54 – Scenario 4 HF Concentrations (Bar Chart)



This data contrasts sharply with the open path FTIR results which showed similar concentrations regardless of the refrigerant. The trending over time points to an issue with the procedure for sampling by this method. It is possible that the sampling lines required a greater volume of flushing with distilled water to remove any residual fluorine ions. This increasing trend does show that each test added to the measurement in the center of the room showing that some amount of HF was generated.

The lines were not blanked and a baseline was not collected between runs. (For future testing, baseline samples (blanks) will be taken between runs that can be used to index the data and confirm that flushing volume is adequate to remove all fluorine ions.)

9.4.3.1. Hydrogen Fluoride in the Hallway (Open path FTIR)

Figure 55 shows the concentration relative to R-410A in each of the four tests. The red line is scaled based by the ratio of the peak R-410A concentration to the peak of the refrigerant used in each test. The blue line represents the buildup to the final average concentration shown in Table 16. The green line is an overlay of the refrigerant mass flow rate. The shape of each plot is similar showing that HF production was similar regardless of the refrigerant in use.

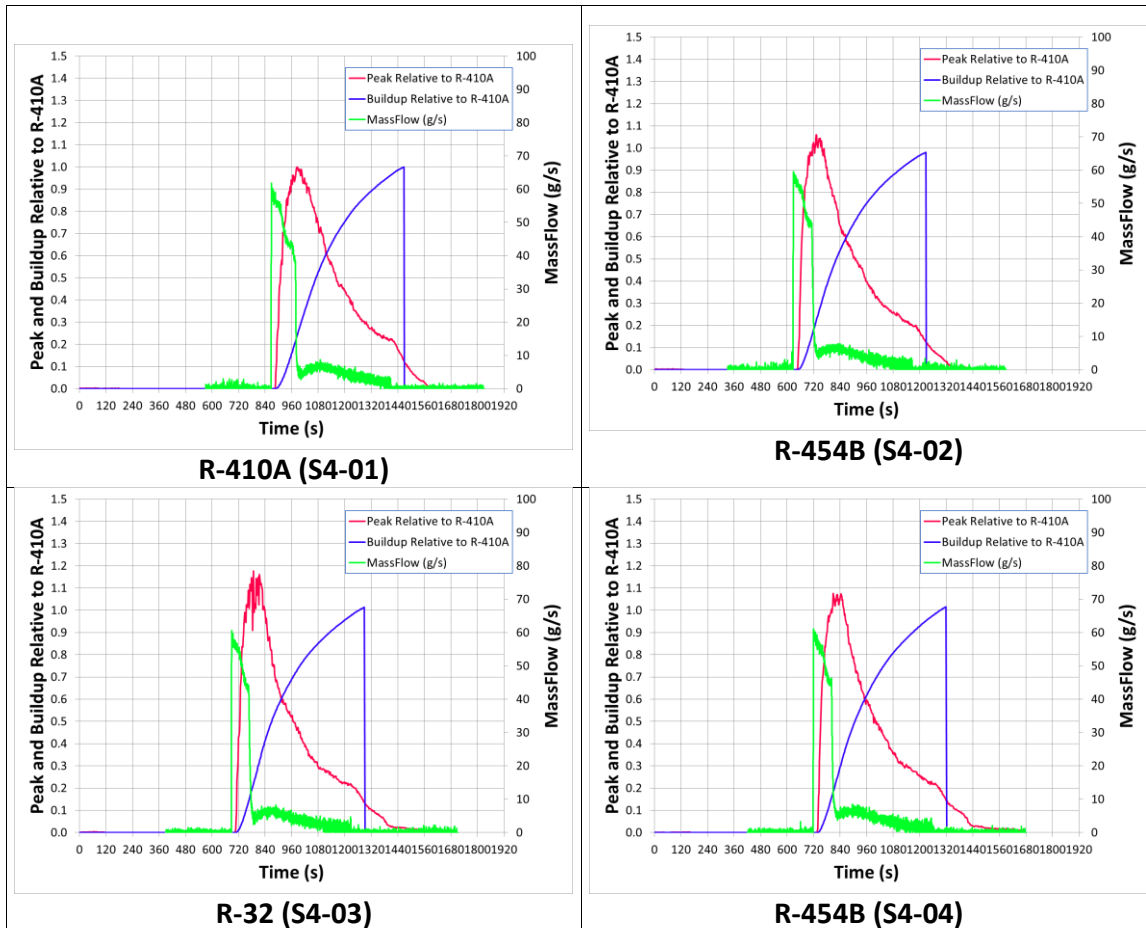


Figure 55 – Scenario 4 Open Path FTIR results relative to R-410A

Table 16 – Scenario 4 Open Path FTIR Results

Refrigerant	Tank Charge (lbm)	Open Path FTIR HF measurement	
		Relative Peak $\pm 14\%$ (k=1)*	Relative Average $\pm 2\%$ (k=1)*
R-410A	20	1.00	1.00
R-454B	17	1.05	0.98
R-32	16	1.18	1.01
R-454B	17	1.07	1.02

See the discussion in section Scenario 1 Results, 9.1.3, regarding these uncertainties.



9.4.4. Scenario 4 Summary

A summary of the results of Scenario 4 are as following:

- Visual observation of the flame during discharge show no difference between R-410A and either R-32 or R-454B.
- There was a small increase in measured heat release rates between 12 and 17 kW over the baseline fire size of 40 kW.
- Heat flux levels increased slightly over the baseline fire size. The increase was generally less than 1 kW/m².
- Temperatures in the room did not exceed 90°C at the ceiling (92 in. level)
- Hydrogen fluoride measurements using the aqueous solution method showed an increasing trend over time. No conclusions on the relative production of acid gases can be made from this data.
- The Open Path FTIR results showed average HF concentrations within 2% of that produced by R-410A. R-32 showed a relative peak that was 18% higher than the peak of R-410A, however the average was within 1% of R410A.

9.4.1. Firefighter Tactical Considerations for A2L Refrigerants Scenario 4

Hazard	Result	Comment
Heat Release Rate	<p>The increase in heat release rate from baseline fire in the sand burner (40 kW) was in the range of 12 to 17 kW for the A2L refrigerants.</p> <p>The increase in size from the R-410A release of 51 kW seems to be an instrumentation error.</p>	<p>The increase in fire size is less than the heat output of a gas log fireplace set (about 25 kW).</p> <p>The overall HRR was about the same as a small plastic trash can fire (50 kW). Refer to Appendix H for more information.</p>
Heat Flux Hallway Entrance	<p>The heat flux as the refrigerant moved through the sand burner flame was less than approximately 1 kW/m².</p>	<p>1 kW/m² is about the same as that provided by the sun. Refer to Appendix H for more information.</p>
Temperature room center	<p>The baseline fire raised ceiling temperatures from ambient (20°C, 68°F) to about 75°C (165°F) before the release. The release caused temperatures at the ceiling to increase between 5°C and 10°C (9°F and 18°F)</p>	
Deflagration	<p>Deflagration was not observed. The size of the sand burner flame was visibly smaller during refrigerant release.</p>	<p>A1 and A2L refrigerants performed in similar manner.</p>
Hydrogen Fluoride (HF) generation	<p>Measurements by the aqueous solution (bubblers) method showed an increasing trend as testing progressed due to sampling errors. As a result, this data is not a reliable indication of fluoride concentrations. Future testing of this nature requires adequate flushing of the sample and the use of a baseline or blank sample. However, the trend in the data does show each refrigerant generated HF gas.</p> <p>Concentration averages by the open path FTIR method show average A2L HF concentrations within 2% of that produced from R-410A.</p>	<p>HF and other halogen compounds are inhalation and skin contact hazards. Contact with contaminated turnout gear can lead to exposures if not properly cleaned.</p> <p>Fire service personnel need to don appropriate PPE for all phases of operation from suppression, to overhaul, investigation, and recovery.</p> <p>Refer to Appendix G for a further discussion of hazards from fluorine compounds.</p>



9.5. Scenario 5

Scenario 5 provides an observation of refrigerant burning when a pool of refrigerant exceeding the allowable quantities is ignited by a flame in a below grade tightly sealed room with no air movement or ventilation. This test room represented a single room (e.g. a basement utility room) in a much larger residence that required a 5-ton AC unit and the associated charge needed to operate. The charge concentration could only occur if the HVAC and integrated mitigation were turned off. This scenario was not in the original plan but was developed cooperatively with AHRI and the fire service representatives to provide an educational tool for the fire service. The design of this scenario was independent of the probability or conditions that could lead to the development of this hazard. The primary purpose was to provide a visual observation of how A1 and A2L refrigerant appears when ignited.

9.5.1. Test Setup

One of the 14x14x8-ft. rooms was used for this scenario. The refrigerant discharge system was modified to minimize turbulence and mixing during the release and allow for the buildup of higher concentrations at the floor level, since R-410A and all A2L refrigerants are heavier than air.

Figure 56 shows the layout of the room. The room door to the hallway was blocked and sealed at the lower half to allow a volume for refrigerant to accumulate.

In this scenario, a diffuser was used to release the refrigerant at floor level. This enabled the refrigerant to release slowly and diffuse in the room. Sensors were used to measure refrigerant concentration at two locations in the room. One set of sensors were close to the release location, and the other set was at the doorway. Open flame ignition sources were located in the room and were ignited remotely.

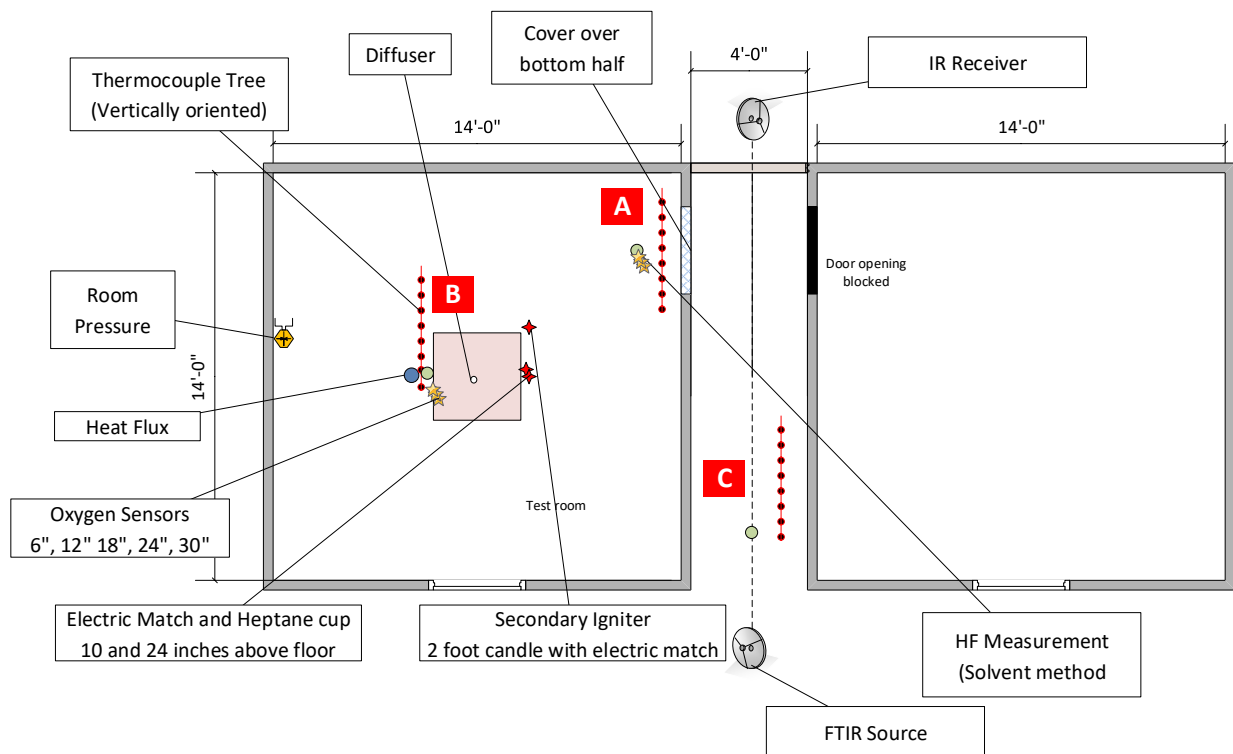


Figure 56 – Scenario 5 room configuration

Figure 57 shows a sketch of the diffuser used in Scenario 5. The diffuser consisted of a Durock® sheet suspended one inch above the floor in the center of the room. An 11-in. square hole was cut in the center of this sheet which allowed for the sand burner case to be inverted over the hole. This arrangement allowed for the refrigerant discharge to expand and lose its initial velocity. It was estimated that the velocity exiting from under the diffuser was in the range of 30 to 40 cm/s.

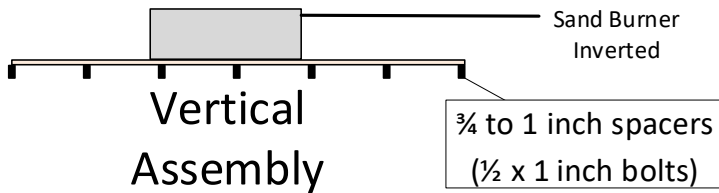
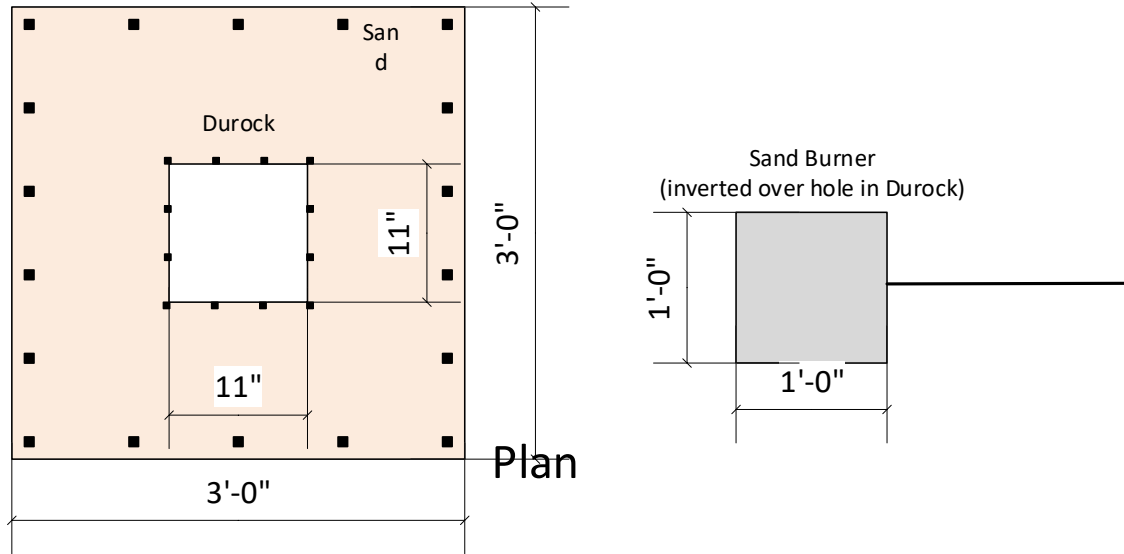


Figure 57 – Diffuser sketch

Oxygen sensors (Apogee Model SO-220) sensors were used to measure refrigerant concentration based on the amount of oxygen displaced. This method was used in the AHRTI 9007-2 project and is fully documented in that report. The formula used to convert the output millivolt signal to refrigerant concentration is shown in Equation 1.

$$x = \left(\frac{S_{init} - S}{S_{init} - S_{zero}} \right) \times 100\% \quad \text{Eqn. 1}$$

Where:

- x Is the refrigerant concentration (% by volume)
- S Is the sensor output (mV)
- S_{zero} Is the sensor output at 0% oxygen (based on Nitrogen) (mV)
- S_{init} Is the sensor output at 20.95% oxygen (mV)

The measurement uncertainty was $\pm 1\%$ ($k=1$) of reading in the range of concentrations between the LFL and UFL for R-32 (14.4% to 29.5%). Temperature corrections were not applied since there was little change in air temperature at the sensor locations which did not affect the linear response of the sensor.

Figure 58 shows the arrangement of the instrumentation in the test room. A total of 10 oxygen sensors were used. At each location the sensors were placed every 6 in. starting at six in. above the floor level.

The acid gas sample probe (stainless steel tube) can be seen in the left-hand photo. Another acid gas sample probe can be seen at the top of the doorway. A third thermocouple tree (not shown) was placed in the hallway exit as shown in Figure 56.

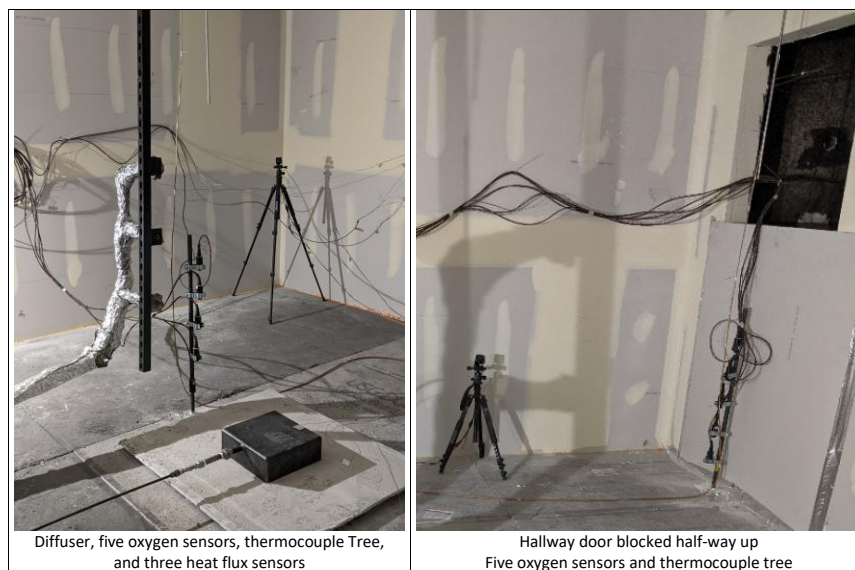
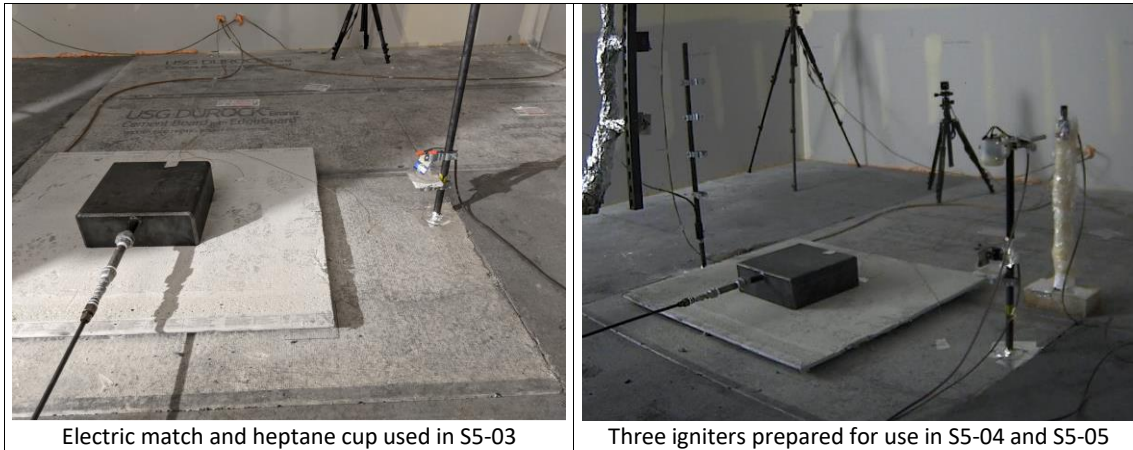


Figure 58 – Scenario 5 Instrumentation

Figure 59 shows the igniters used during the ignition sets, S5-03, S5-04, and S5-05. A single igniter with the cup a 6 in. above the floor was used in the R-32 test S5-03. This test failed to ignite because the flames started at a level in the room above the UFL of R-32. The decision was made to install three igniters for the last two tests with the intention to light them sequentially if needed. The original igniter was raised to the 10 in. level (first to be ignited). The second igniter was a heptane cup at the 24 in. level. The third igniter was a 24 in. rod wrapped in cheese cloth and paper towels, a final layer of plastic. The third igniter was filled from the top with 30 ml of heptane. The cups of the other two igniters were filled with the same amount of heptane.



Electric match and heptane cup used in S5-03

Three igniters prepared for use in S5-04 and S5-05

Figure 59 – Scenario 5 Igniters

9.5.2. Test Procedure

The test procedure in this scenario consisted of the following generalized steps:

- Shutdown exhaust from the test room to provide static conditions in the test room
- Charge the release system with the 16 lbm of R-32 or R-410A
- Arm the electric matches (if used in this test)
- Start data acquisition and collect quiescent state data for 5 minutes (t = 0 min)
- Start the discharge (t = 5 min)
- Stop the discharge (t = 14 min)
- Start the first electric match (t = 14 min + 10 sec)
- Continue taking data for 20 minutes (t = 34 min)
- Start exhaust from the test room and monitor conditions for safe entry

A full description of the Scenario 5 test procedure is contained in Appendix D.

Table 17 provides the test matrix for Scenario 5. The first test, S5-0_NI was used to verify the instrumentation and the operation of the diffuser. A leak was found in the test room in the connection to the sand burner. This was repaired and the test series continued.

Table 17 – Scenario 5 Test Matrix

Test#	Refrigerant	Tank Mass (lbm)	Comment
S5-0_NI	R-32	16	Leak near the sand burner case. No video taken
S5-01	R-32	16	Concentration test
S5-02	R-410A	16	Concentration test
S5-03	R-32	16	No ignition at 6 in. level
S5-04	R-32	16	Ignition test with propagation, but no deflagration
S5-05	R-410A	20	Small amount of local ignition

9.5.3. Results

Heat Release Rates were not recorded in Scenario 5 because the exhaust system was shut down until after completion of the test. This was done to provide as little air movement as possible in the test room.

Refrigerant Concentration Measurements (without ignition)

Placement of the ignition sources in this scenario depended on finding local concentrations between the LFL and UFL. Figure 60 shows the concentrations measured for R-32. The LFL and UFL values plotted are 14.4% and 29.5%. The LFL and UFL are based on refrigerant at 23°C and 50 %RH and could vary at the actual temperature conditions seen during this test. The temperature at the level of the igniter was between 21°C and 22°C, so LFL and UFL values were not expected to be significantly different than reported in ASHRAE 34. The data shows that there is a flammable mixture somewhere between 6 and 12 in. above the floor. Data is shown for both the room center and at the hallway door. This data shows that the pool of refrigerant was nearly uniform at each level above the floor. Data for the 24 in. and 30 in. heights are not shown since it was less than 2% at the end of this 40- minute test.

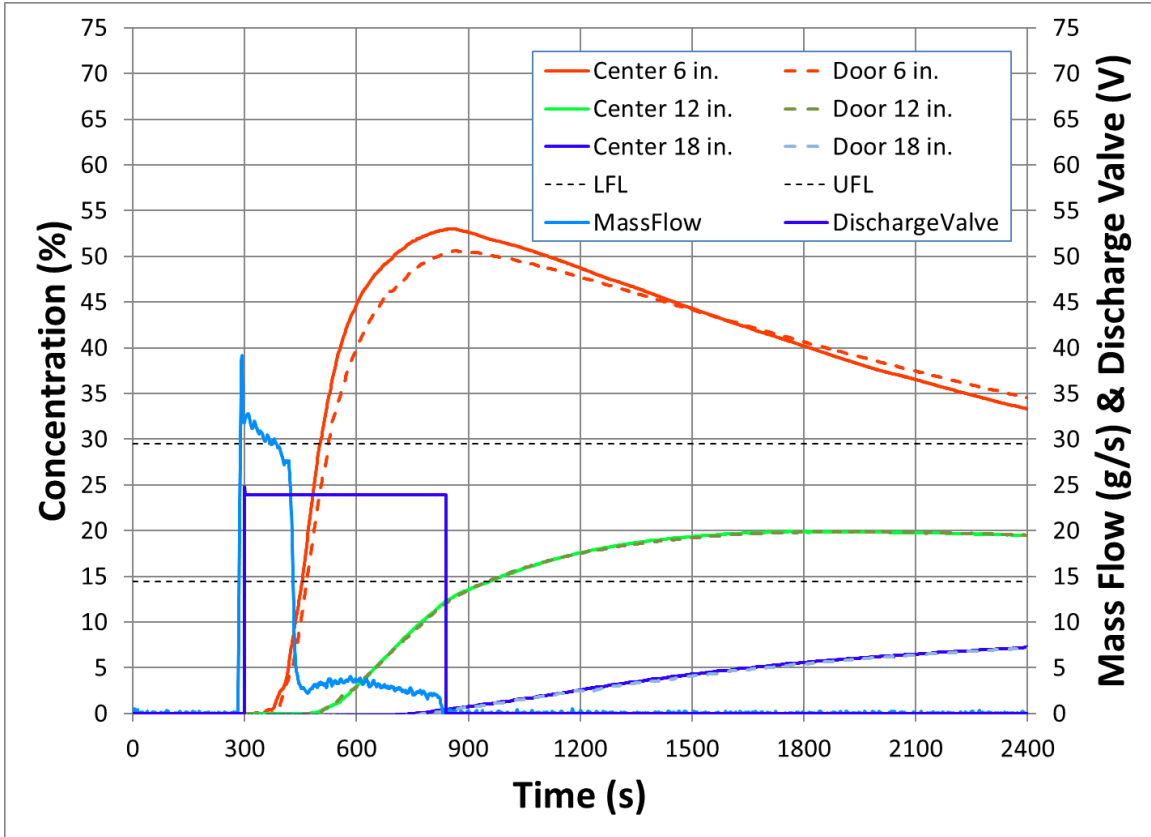


Figure 60 – R-32 Refrigerant concentration test (S5-01)



Figure 61 shows the concentrations measured for R-410A. The LFL and UFL (17% and 20%) values plotted in the chart are based on R-410A at 60°C and 20% relative humidity (RH) reported in “Risk Assessment of Mildly Flammable Refrigerants” [7]. Combustibility of the gas mixture will vary with local temperatures near ignition sources. Note that R-410A does not have flammability limits at either 23°C with 50% RH or 60°C with 7% RH, the conditions used for ASHRAE 34 flammability classification tests [3], and only begins to exhibit flammability limits at the higher 60°C temperature when adding more than twice the absolute moisture content. Similar to R-32, the concentrations at 24 and 30 in. are not shown because they were less than 2% at the end of this 40-minute test. This data shows that an ignition source placed at the right height may be able to heat the R-410A enough that it will ignite.

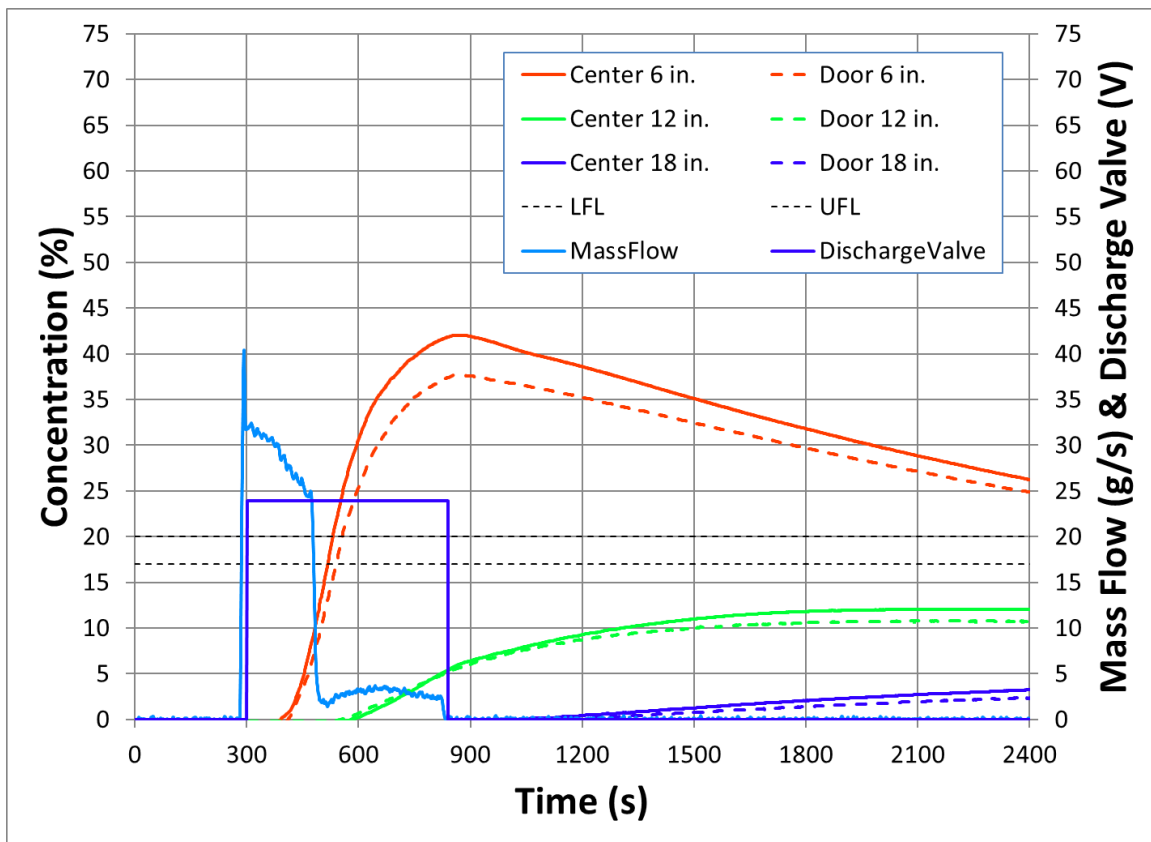


Figure 61 – R-410A Refrigerant concentration test (S5-02)

All but one oxygen sensor was removed for the ignition tests because HF exposure can destroy the sensor. The right-side photo in Figure 59 shows the location of this single sensor at the 6 in. level next to the diffuser assembly.

Refrigerant Concentration Measurements (with igniters)

The first R-32 test (S5-03) did not result in ignition because the electric match and heptane pan did not have enough oxygen to ignite. It was estimated that oxygen concentration was less than 11%. Most hydrocarbons including heptane cannot ignite below 12%. While the electric match did flare to a higher level, its duration was too short to ignite the flammable layer. The left-side plot in Figure 62 shows the R-32 concentration in the first ignition test (S5-03, Yellow Line) had climbed to 55% meaning that oxygen

concentration had been reduced to about 9.5%. The next R-32 test did ignite (Red line). The rapid drop in concentration was due to the resulting fire pulling fresh air toward the sensor.

The right side of the figure shows R-410A concentration. The graph shows a slight disturbance from the igniters causing the concentrations to be stirred. There was not propagation of flaming in the R-410A test beyond the immediate vicinity of the igniters.

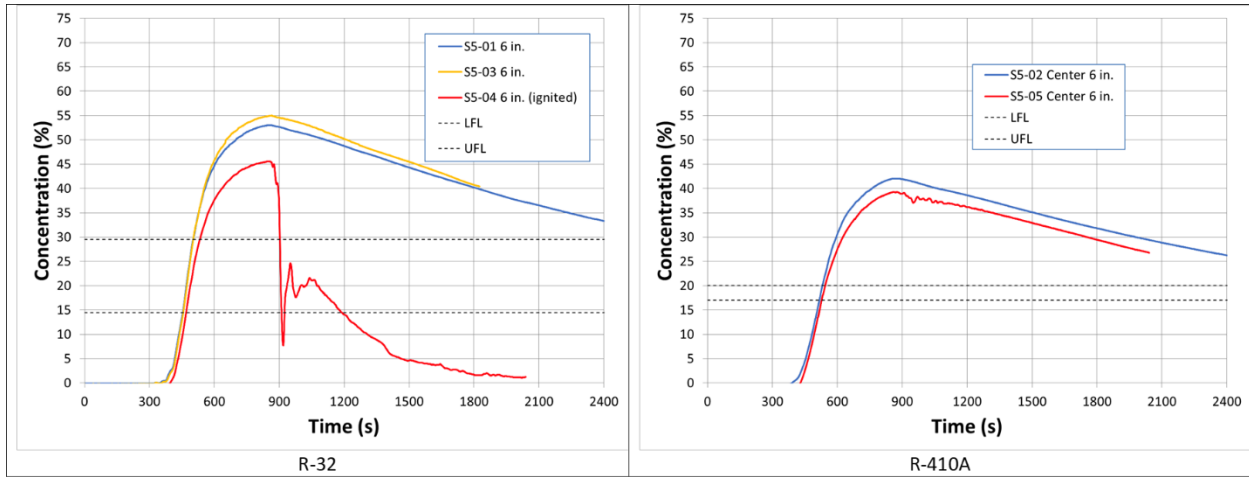


Figure 62 – Concentrations at the 6 in. level for all Scenario 5 tests

Visual Observations

Figure 63 shows the ignition sequence of R-32. While difficult to observe from still images, these flames developed slowly over a period of 40 seconds. At ignition + 1 second, the photo clearly shows that the flame is unable to spread downward to the floor level because the concentrations were above the UFL. This behavior is evident even at ignition + 40 seconds. The flames did travel toward the door due to buoyant and convective forces. The second and third igniters were not intentionally triggered but ignited due to the propagation of flames from the first igniter location.

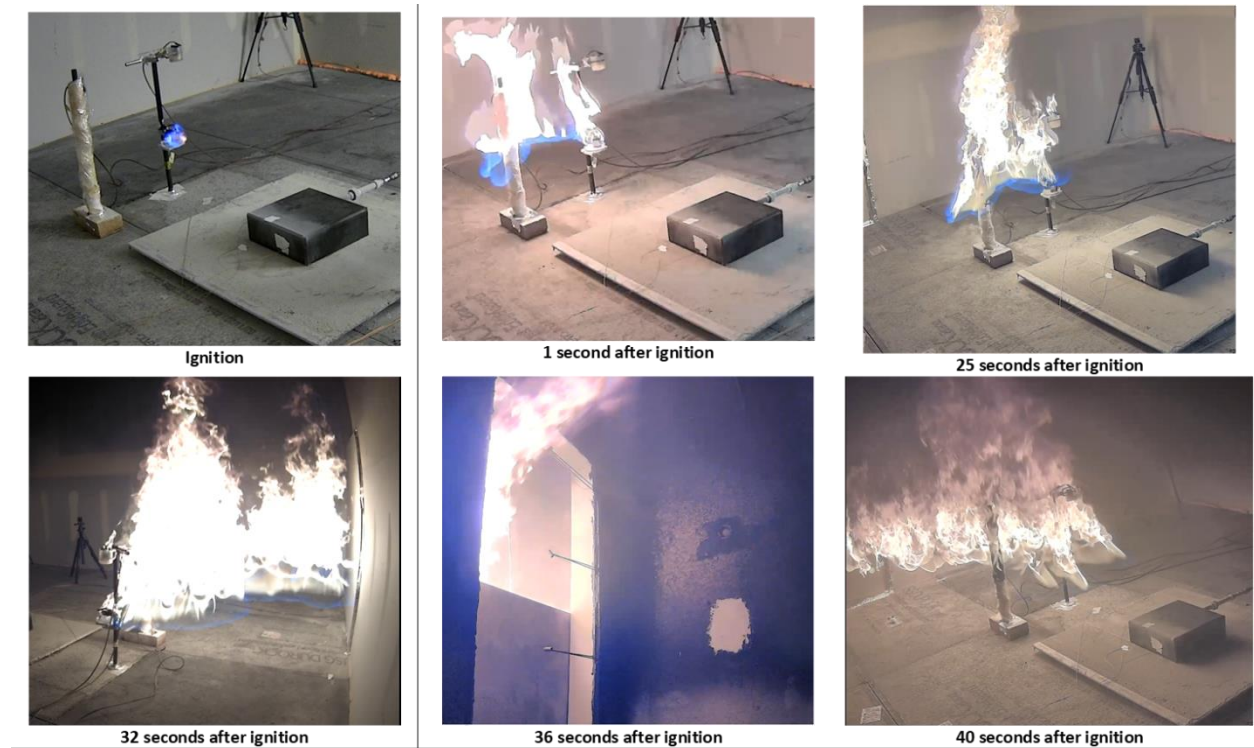


Figure 63 – R-32 Ignition (S5-04)

Figure 64 shows the results of the attempt to ignite the R-410A pool. The sequence shows some combustion of R-410 at ignition and at +1 second (blue tinged flame). The flame did not propagate away from the igniter. At +32 seconds the only flaming is from the heptane in the igniter pan. The other two igniters were triggered, but there was no propagation observed. At ignition + 140 seconds a thick layer of dense smoke was observed above the floor level. This indicates that this smoke was lighter than the layer below, but heavy enough that it could not move upwards. This stratification due to thermal decomposition of the R-410A components from exposure to the igniter flames. The composition of this smoke layer is unknown.

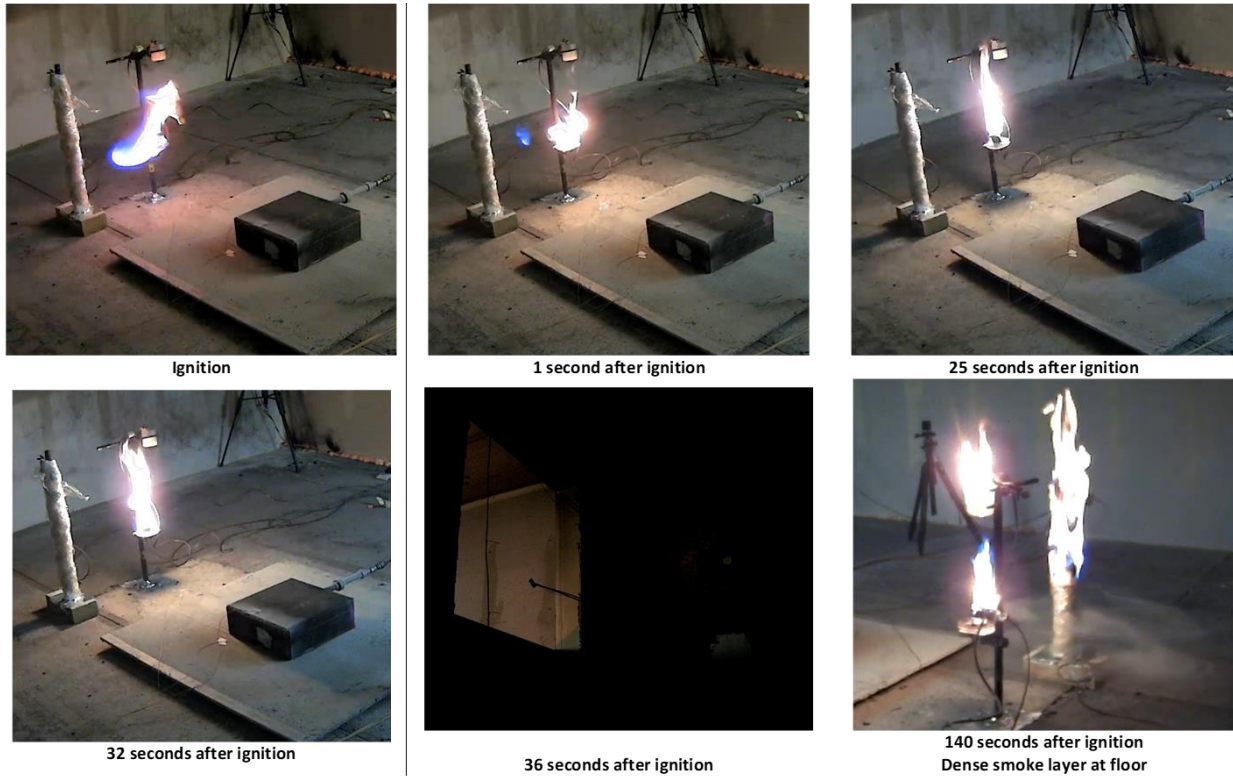


Figure 64 – R-410A Ignition (S5-05)

Heat Flux

The heat flux gages were located three feet away from the igniters, on the other side of the diffuser. The R-32 (S5-04) test with ignition resulted in a peak heat flux of 15 kW/m² about 70 seconds after ignition. For the R-410A test (S5-05), the only source of heat flux came from the igniters and was too low to register any increase in heat flux.

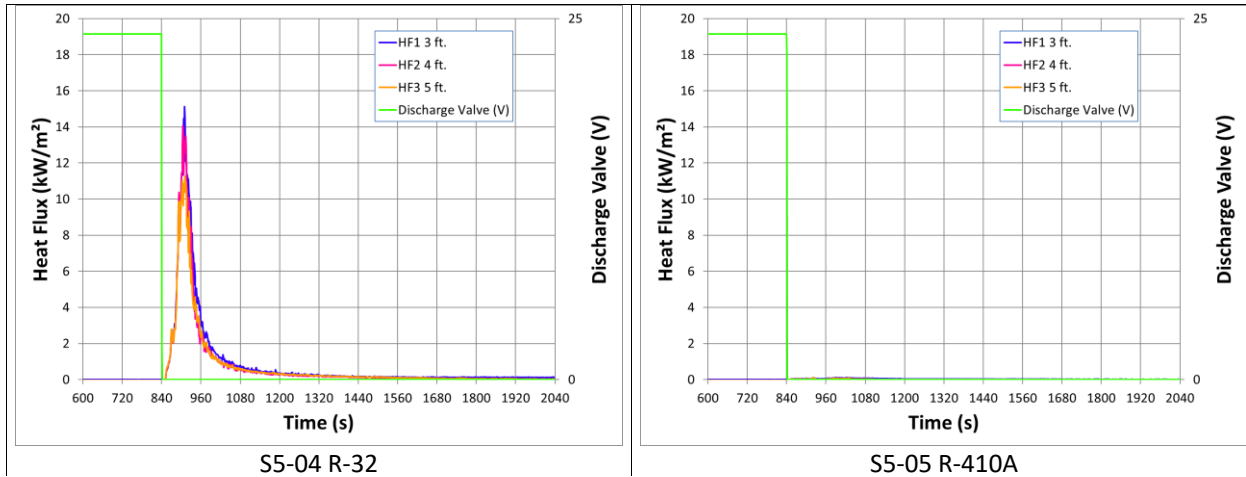


Figure 65 – Scenario 5 Heat Flux Measurements

Temperature

The temperatures at the diffuser were measured with thermocouples to address the question of whether the resulting mixture with room air would be too cold to ignite. Figure 66 shows some temperatures at the diffuser dropped to nearly -50°C, and then began recovering shortly after completion of the refrigerant discharge.

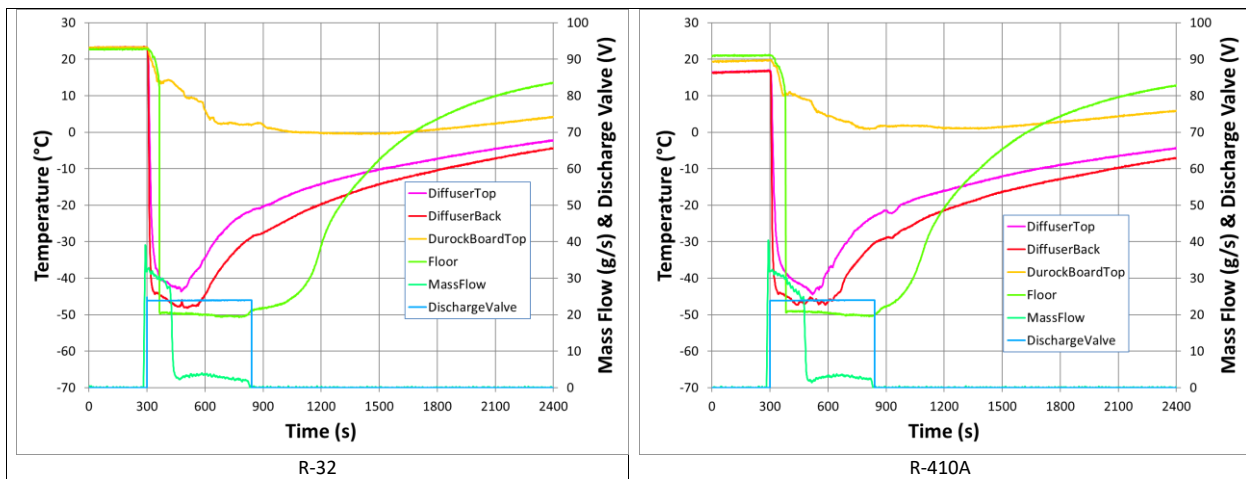


Figure 66 – Temperatures at various locations on and near the diffuser

Figure 67 shows that thermocouples in the center were only slight affected by the discharge of the refrigerant. The largest drop (-1°C) in temperature occurred at the 8-in. level. The higher levels were only slightly affected

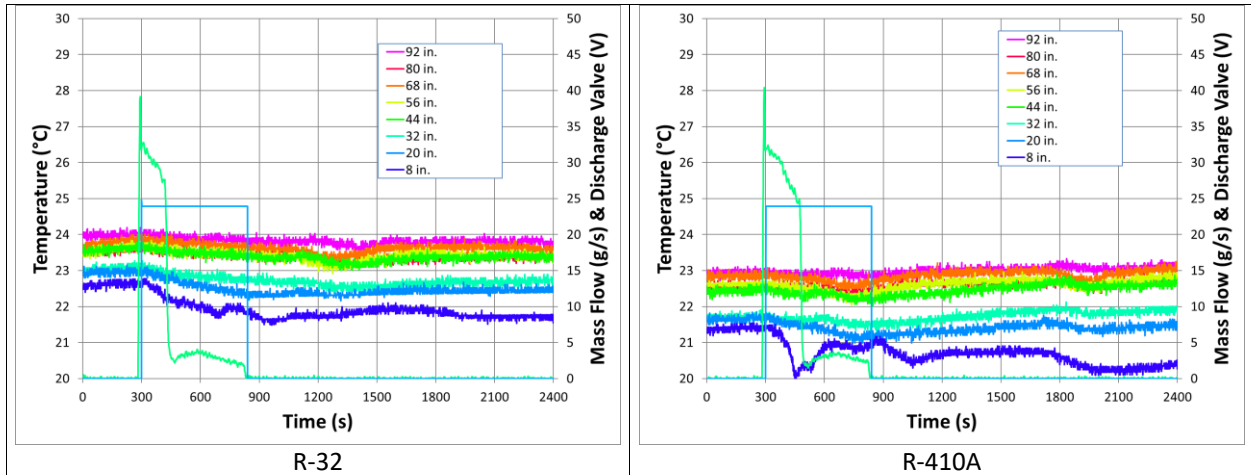


Figure 67 – Room Center temperatures following the refrigerant discharge

Temperature in Ignition Tests (S5-03, S5-04, S5-05)

Figure 68 shows the room center temperatures from the two ignition tests. The slight increase in temperatures in the R-410A test are due entirely to the igniter flames.

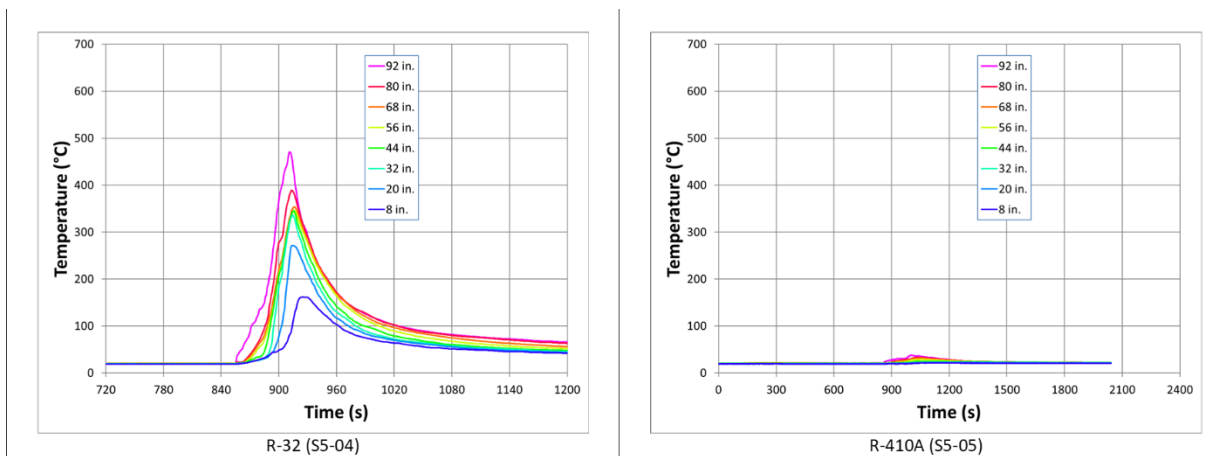


Figure 68 – Temperatures resulting from ignition tests

Hydrogen Fluoride Using Aqueous Solution

As noted in Scenario 4, there may be an issue with the sample line flushing procedure which can affect the results of subsequent tests. Table 18 shows the average HF concentrations in air during the 20 minutes sampling period after the initiation of the flames. Because of the possibility of fluorine ions remaining in the sample lines after the flush following the R-32 test, the reported concentrations from the R-410A test were likely to be lower than measured.

Table 18 – Scenario 5 HF Average Concentrations in Air

Test #	Refrigerant	Hallway Door (ppm v/v)*	Test Room Center (ppm v/v)
S5-04	R-32	1280	1170
S5-05	R-410A	200	240

* -- The measurement uncertainty of these concentrations was $\pm 20\%$ (k=1) excluding the amount HF loss in the collection hood and concentrations remaining in the sample tubing. This additional uncertainty could not be quantified. See section 7.5.2 for discussion.

Hydrogen Fluoride in the Hallway (Open path FT-IR)

Figure 69 shows the concentrations measured by the open path FTIR instrument. Comparison of these charts show the peak concentration of HF in the R-32 test (S5-04) was twice as high as the R-410A test (S5-05). One reason for the difference is the transport time of the gases through the FTIR beam. The ignition and subsequent combustion of R-32 with flame spread throughout the room generated more HF than the attempted ignition of R-410A with only localized combustion, and also resulted in higher temperatures than the R-410A test. As a result of the expansion of these gases, the transport time through the FTIR beam was much shorter than that of R-410A gases. These concentration measurements are not directly comparable, but simply show that the R-32 ignition resulted in higher concentrations of HF gas. Refer to Section 7.5.1 for discussion.

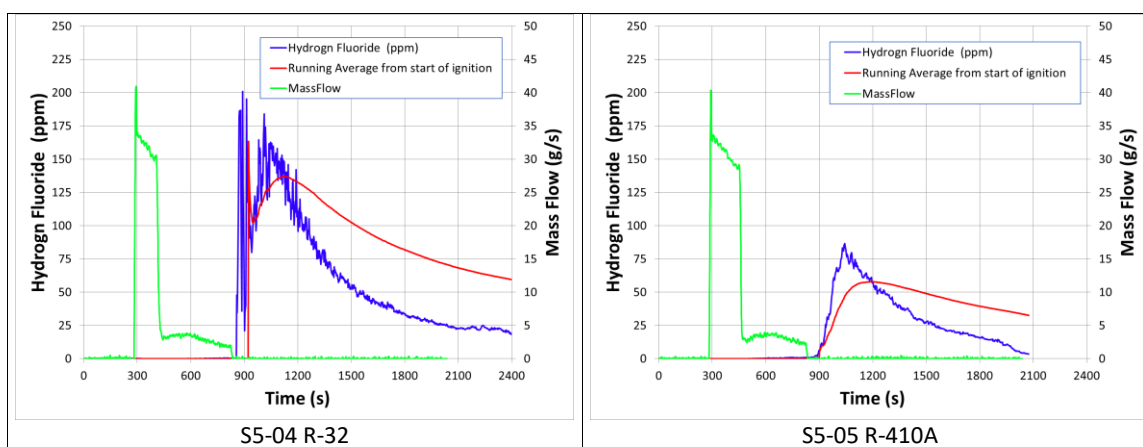


Figure 69 – Scenario 5 Open Path FTIR concentrations of HF

9.5.4. Scenario 5 Summary

Observations on the results of Scenario 5 include the following:

- High concentrations of refrigerants at the floor level did not ignite
- The diffusion of refrigerant into the room did not significantly lower room temperatures at a height of 8 inches and above
- The diffusion of refrigerant into the room significantly lowered the floor temperature
- R-410A showed some combustion but only in close proximity to the igniter flame
- The R-410A showed the development of a stratified layer of smoke above the floor level meaning it was too dense to rise due to buoyancy, but too light to drop through the denser layer underneath.
- The R-32 ignition test was relatively slow to develop compared to similar tests in the AHRI 9007-2 (propane) project. A typical propane fire in that project lasted no more than 7 seconds, while the R-32 fire was still developing at ignition + 40 seconds.
- The refrigerant moved towards the flame as it burned

9.5.5. Firefighter Tactical Considerations for A2L Refrigerants Scenario 5

Hazard	Result	Comment
Refrigerant Concentration	A slow leak in a below grade, closed room with no air movement and with code required mitigation not working can build up high concentrations at the floor level since these gases are heavier than air. These refrigerants are also colorless and odorless.	Ventilation using typical fire service methods is needed if a suspected buildup has occurred.
Heat release rate and Visual Observation	Heat Release was not measured. Flames stayed above the floor level due to concentrations above the UFL near the floor.	Visually the fire in test S5-04 grew very slowly giving firefighters time to observe and react to the situation
Heat Flux in the room	Heat flux peaked to 15 kW/m ² at 3 feet distance from the ignition source.	Eight seconds of skin exposure to this heat flux is sufficient to cause second degree burns. Refer to Appendix H for more information..
Temperature room center	When ignited (S5-05) the combustion of R-32 caused temperatures to rise to 150°C (300°F) at the 8 in. level. Temperatures over 300°C (540°F) were observed at levels 32 in. and above.	The temperatures developed slowly according to the slowly developing fire. Temperatures above 100°C endured for as long as 4 minutes.
Deflagration	Deflagration was not observed.	The failure to ignite the R-32 concentrations in test S5-03 indicate the difficulty of creating the conditions for an A2L refrigerant to ignite.
Hydrogen Fluoride (HF) generation	All Scenario 5 tests, with refrigerant ignition and with attempted refrigerant ignition, showed measurable HF concentrations at potentially hazardous levels within the room. The peak concentration of HF in the R-32 test (S5-04) was twice as high as the R-410A test (S5-05).	HF and other halogen compounds are inhalation and skin contact hazards. Contact with contaminated turnout gear can lead to exposures if not properly cleaned. Fire service personnel need to don appropriate PPE for all phases of operation from suppression, to overhaul, investigation, and recovery. Refer to Appendix G for a further discussion of hazards from fluorine compounds.



10. Testing for Surface Contamination

The possibility of hydrogen fluoride (HF) deposition on surfaces was assessed by using filter paper wipes dampened with distilled water to collect swipe samples at eight representative locations within each test compartment. The swiped area was approximately the same for each location, about 100 cm². Compartment 1 was sampled after execution of all Scenario 5 tests including the S5-04 test R-32 refrigerant was ignited. Compartment 2 was sampled after execution of Scenario 2 (S2-04) testing where the compartment was brought to a fully developed fire and R-32 refrigerant was then injected into the hot gas layer.

The wipes were then deposited into 50 ml of distilled water and allowed to soak and release their contents into the solution. The swabs were then mixed 50 mL of ionic strength adjuster to prepare the sample for measurement. The samples were then tested for fluorine ion concentrations according to the procedure in Appendix E.

Figure 70 shows the locations where surface samples were taken. The walls in this room had been rebuilt before Scenario 5 was started, however, the fire door where two samples were taken had not been cleaned throughout the entire test program. The door handle itself was replaced after the flashover tests, but the door was not cleaned between tests.

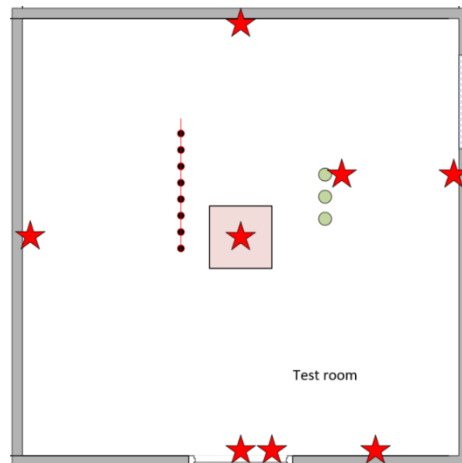


Figure 70 – Scenario 5 surface sample locations (North is the left side in the figure)

Table 19 shows the measured fluoride ion concentrations from each sample location as well as the measure of $\mu\text{g}/\text{cm}^2$ (assuming a 100 cm^2 sampling area).

Table 19 – Surface wipe sample concentrations following Scenario 5 tests

Location	Measured Concentration (ppm g/g)*	Surface Contamination ($\mu\text{g}/\text{cm}^2$)
South Wall	12	12
North Wall	8	8
East Wall	18	18
West Wall	15	15
Door Handle	112	112
Inside of Door vent	42	42
Top of Diffuser	129	129
Ignitor	24	24

* -- The measurement uncertainty of these concentrations was $\pm 20\%$ ($k=1$) excluding the amount HF loss from incomplete removal of samples at the swab site. This additional uncertainty could not be quantified due to nature of the surfaces being swabbed, reaction with the calcium on those surfaces and the shape of door handles.

Figure 71 shows the location of the surface samples taken following the ventilation limited fire with an R-32 internal release in the air handler. The walls had been rebuilt before this test so any measured concentrations from the walls were deposited during this test. The inside surface of the door leaf had not been cleaned during the entire test program and may have had a surface accumulation from prior tests.

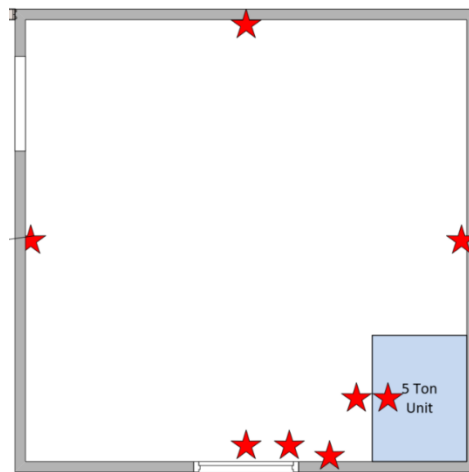


Figure 71 – R-32 (S2-04) Post-test sample locations (North is the left side in the figure)

Table 20 shows the measured fluoride ion concentrations from each sample location.

Table 20 – Surface wipe sample concentrations follow Scenario 2 R-32 Inside release (S2-04)

Location	Measured Concentration (ppm g/g) *	Surface Contamination (µg/cm ²)
North Wall	3	3
South Wall	4	4
West Wall	3	3
East Wall	4	4
Door Vent	10	10
Door Handle	1	1
Unit Siding	2	2
Inside Unit	2	2

* -- The measurement uncertainty of these concentrations was ±20% (k=1) excluding the amount HF loss from incomplete removal of samples at the swab site. This additional uncertainty could not be quantified.

10.1. Firefighter Tactical Considerations for deposition of HF on surfaces

Hazard	Result	Comment
Hydrogen Fluoride (HF) generation	All surfaces tested showed some measure of fluoride ions (between 1 and 126 ppm, 1 and 226 µg/cm ²).	Hazardous surface contaminants remain in the fireground after overhaul. PPE is needed for investigation. Decontamination of surfaces should be considered as part of the recovery efforts.

11. References

- [1] ASHRAE, Standard 34-2019, Designation and Safety Classification of Refrigerants, Atlanta: ASHRAE, 2019.
- [2] ASHRAE, "Addendum U to Standard 34-2019," in *Designation and Safety Classification of Refrigerants*, Atlanta, ASHRAE, 2019.
- [3] ASHRAE, "Addendum F to Standard 34-2019," in *Designation and Safety Classification of Refrigerants*, Atlanta, ASHRAE, 2019.
- [4] P. V. Forster and et al., "Table 2.14, Changes in Atmospheric Constituents and in Radiative Forcing," in *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York, Cambridge University Press, 2007.
- [5] NIST, "NIST Technical Note 1474 Thermal Environment for Electronic Equipment Used by First Responders," 2006.
- [6] NFPA, "NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting," 2018.
- [7] E. Hihara, "Risk Assessment of Mildly Flammable Refrigerants.," 2014.
- [8] Airgas, "Hydrogen Fluoride Safety Data Sheet," 2018.
- [9] e. a. Seong-Yong Cho, "Acute Symptoms in Firefighters who Participated in Collection Work after the Community Hydrogen Fluoride Spill Accident," *Annals of Occupational and Environmental Medicine*, vol. 25(1), 2013.
- [10] EPA, "Hydrogen fluoride Results - AEGL Program," 2004. [Online]. Available: <https://www.epa.gov/aegl/hydrogen-fluoride-results-aegl-program>. [Accessed 22 2021].
- [11] P. Gandhi, G. Hunter, R. Haseman and B. Rodgers, "AHRTI Report No. 9007-1 Benchmarking Risk by Whole Room Scale Leaks and Ignitions Testing of A2L Refrigerants," AHRTI, Arlington, VA, 2017.
- [12] NIOSH, "Permissible Exposure Limits - Annotated Tables: Z-2 Table," 2019. [Online]. Available: <https://www.osha.gov/annotated-pels/table-z-2>. [Accessed 24 January 2021].

Appendix A Scenario 1 Test Procedure

AHRI Scenario 1 Checklist (Rev4 – 10/29/2020)

Date: _____ Test #: _____ Test Start Time: _____

Pre-test lab humidity: _____ Pre-test lab temperature: _____ Refrigerant:

Master Checklist

- Initial Preparations
- Test Setup
- Propane Discharge
- Refrigerant Discharge
- Test End

Initial Preparations:

- RTO warmed up
- Valves power supply on
- Transducers power supply on
- Load cell power supply on
- Power-on DAQ, DVR, monitor
- Power on FTIR
- FTIR alignment OK
- FTIR Background
- Power-on tank heater. Test temperature: _____
- Set distance/height of burner from discharge nozzle. Distance: _____; height: _____
- FOR NATURAL DECAY TESTS: transfer 15lbs of test refrigerant to an empty tank
- Hang the refrigerant tank on the load cell
- Connect pressure transducer to tank outlet
- DAQ – all instrument values nominal
- Fill each bubbler with 50 mL of DISTILLED water
- Bubbler line connected
- Label sample bottles for transferring the bubbler solutions after the test
- Calorimeter sample pump running
- Calorimeter chiller running
- Calorimeter oxygen analyzer span calibrated
- Marquee in place

- Top off liquid N2
- SAFETY: Building 11 staff aware of testing

Test Setup:

- RTO set to Test Mode for ADD laboratory
- Discharge system vacuumed out (98% vacuum or better)
- Connect the tank to the discharge system via the refrigerant hose
- Charge system
- Note settled weight of tank assembly (hanging hose, heater, etc). Weight: _____ kg
- System pressure stabilized to test pressure
- SAFETY valve is OPEN
- Discharge system manual valves OPEN
- Manual valve near discharge nozzle CLOSED
- Bubbler three-way valve in SAMPLE position
- Start bubbler pump. Adjust flow to 1 SCFH (0.5 L/min).
- Start circulating water flow to the heat flux gauges
- Start water flow to the acid gas sample heat exchanger
- Check positioning and focus of cameras
- Check position of discharge nozzle
- SAFETY: Locate all staff outside the test lab except the designated personnel for test start
- Set NI system to HIGH SPEED and test time of 9999 seconds
- Enable camera recording
- Begin recording on BOTH DAQs
- Vacuum release set to "TEST"

Propane Discharge

- Open propane tank valves. They should be close to 10 psi
- Ignite paper in burner
- Open burner valve
- Open final discharge system valve near nozzle
- Set rotameter flow to 180 SCFH for 120 kW

Refrigerant Discharge

- SAFETY: Set DO NOT ENTER signage and strobe on lab door
- Allow two minutes of pre-data then open the DISCHARGE valve to start the test
- Open the DISCHARGE valve

Test End



- FOR STEADY STATE DISCHARGE: Flow refrigerant for 140 seconds to release approximately 15 lbs of refrigerant
- FOR NATURAL DECAY DISCHARGE: Flow refrigerant for 240 seconds or until flaming ceases
- Close DISCHARGE valve to end test
- Stop DAQ recording after 5 minutes of post-discharge data
- Relieve bubbler vacuum
- SAFETY: Allow HF background to return to normal before entering lab
- Transfer the contents of each bubbler to the labeled sample bottles.
- Bubbler three-way valve to BACKFLUSH setting
- Backflush sampling line with 50 mL DISTILLED water and collect sample



Appendix B Scenario 2 Test Procedure

AHRI Scenario 2 Checklist (Rev4 – 11/19/2020)

Date: _____ Test #: _____ Test Start Time: _____

Pre-test lab humidity: _____ Pre-test lab temperature: _____ Refrigerant:

Master Checklist

- Initial Preparations
- Test Setup
- Test
- Post Test

Initial Preparations:

- RTO warmed up
- Power supplies on
- Power-on DAQ, DVR, monitor
- Power on FTIR
- Power-on tank heater. Test temperature: _____
- Transfer test refrigerant to test tank
- Hang the refrigerant tank on the load cell
- Connect pressure transducer to tank outlet
- Fill each bubbler with 50 mL of DISTILLED water
- Bubbler lines connected
- Label sample bottles for transferring the bubbler solutions after the test
- Calorimeter sample pump running
- Calorimeter chiller running
- Calorimeter oxygen analyzer span calibrated
- Marquee in place
- Top off liquid N2
- SAFETY: Building 11 staff aware of testing
- Spot check all radiometers, thermocouples and BDPs
- DAQ – all instrument values nominal

Test Setup:

- RTO set to Test Mode for ADD laboratory
- Discharge system vacuumed out (98% vacuum or better)

- Connect the tank to the discharge system via the refrigerant hose
- Charge system
- Note settled weight of tank assembly (hanging hose, heater, etc). Weight: _____ kg
- System pressure stabilized to test pressure
- SAFETY valve is OPEN
- Discharge system manual valves OPEN
- Manual valve near discharge nozzle CLOSED
- Start bubbler pump. Adjust flow to 1 SCFH (0.5 L/min) on each.
- Start circulating water flow to the heat flux gauges
- Start water flows through heat exchangers
- Check positioning and focus of cameras
- Confirm bubblers through cameras
- Check position of discharge nozzle
- Check electric match
- Sprinkler line pressurized
- Open test room and hallway manual valves
- SAFETY: Check function of sprinkler valves
- FTIR alignment OK
- FTIR Background
- Check TEST START function
- SAFETY: Locate all staff outside the test lab
- Set NI system to HIGHSPEED at 10hz and 99999 test time
- Enable camera recording
- Begin recording Edge for 60 seconds of pre-data
- Begin recording NI and FTIR at T=0

Test

- SAFETY: Set DO NOT ENTER signage and strobe on lab door
- Vacuum release set to "TEST"
- Edge Start T= -1 minute
- NI and FTIR start at T=0
- Ignition and TEST START at T = 5 min
- Discharge at T = 11 min
- STOP discharge at T = 14 min
- Actuate TEST ROOM sprinkler at T = 16 mins
- Switch to CONTINUOUS NI data at T = 17 mins

Post Test

- Relieve bubbler vacuum

- SAFETY: Allow HF background to return to normal before entering lab
- Transfer the contents of each bubbler to the labeled sample bottles.
- Backflush each 12ft sampling line with 50 mL of TISAB buffer solution and collect in BOTTLE 1 sample,

Appendix C Scenario 4 Test Procedure

AHRI Scenario 4 Checklist (Rev2 – 11/12/2020)

Date: _____ Test #: _____ Test Start Time: _____

Pre-test lab humidity: _____ Pre-test lab temperature: _____ Refrigerant:

Master Checklist

- Initial Preparations
- Test Setup
- Propane Discharge
- Refrigerant Discharge
- Test End

Initial Preparations:

- RTO warmed up
- Power supplies on
- Power-on DAQ, DVR, monitor
- Power on FTIR
- Power-on tank heater. Test temperature: _____
- Set distance/height of burner from discharge nozzle. Distance: _____; height: _____
- Transfer test refrigerant to test tank
- Hang the refrigerant tank on the load cell
- Connect pressure transducer to tank outlet
- Fill each bubbler with 50 mL of DISTILLED water
- Bubbler lines connected
- Label sample bottles for transferring the bubbler solutions after the test
- Calorimeter sample pump running
- Calorimeter chiller running
- Calorimeter oxygen analyzer span calibrated
- Marquee in place
- Top off liquid N2
- SAFETY: Building 11 staff aware of testing
- Spot check all radiometers, thermocouples and BDPs
- DAQ – all instrument values nominal

Test Setup:



- RTO set to Test Mode for ADD laboratory
- Discharge system vacuumed out (98% vacuum or better)
- Connect the tank to the discharge system via the refrigerant hose
- Charge system
- Note settled weight of tank assembly (hanging hose, heater, etc). Weight:_____kg
- System pressure stabilized to test pressure
- SAFETY valve is OPEN
- Discharge system manual valves OPEN
- Manual valve near discharge nozzle CLOSED
- Start bubbler pump. Adjust flow to 1 SCFH (0.5 L/min) on each.
- Start circulating water flow to the heat flux gauges
- Check positioning and focus of cameras
- Confirm bubblers through cameras
- Check position of discharge nozzle
- FTIR alignment OK
- FTIR Background
- SAFETY: Locate all staff outside the test lab except the designated personnel for test start
- Set NI system to CONTINUOUS
- Enable camera recording
- Begin recording on BOTH DAQs AND FTIR at same time
- Vacuum release set to "TEST"

Propane Discharge

- Open propane tank valves. They should be close to 10 psi
- Ignite paper in burner
- Open burner valves
- Open final discharge system valve near nozzle
- Set rotameter flow to 60 SCFH for 40 kW (total HRR)

Refrigerant Discharge

- SAFETY: Set DO NOT ENTER signage and strobe on lab door
- Allow room conditions to stabilize with fire
- Change NI system to HIGHSPEED with test time of 99999 seconds
- Flip TEST START toggle switch at same time
- Allow five minutes of pre-data
- Open the DISCHARGE valve

Test End



- Flow refrigerant for 9 minutes
- Close DISCHARGE valve to end test
- Stop DAQ recording after 5 minutes of post-discharge data
- Relieve bubbler vacuum
- SAFETY: Allow HF background to return to normal before entering lab
- Transfer the contents of each bubbler to the labeled sample bottles.
- Backflush each 12ft sampling line with 50 mL of _____ and collect in BOTTLE 1 sample

Appendix D Scenario 5 Test Procedure

AHRI Scenario 5 Test Checklist (Rev 1 – 12/1/2020)

Date: _____ Test #: _____ Test Start Time: _____

Pre-test lab humidity: _____ Pre-test lab temperature: _____ Refrigerant:

Master Checklist

- Initial Preparations
- Test Setup
- Test
- Post Test

Initial Preparations:

- RTO warmed up
- Power supplies on
- Power-on DAQ, DVR, monitor
- Power on FTIR
- Power-on tank heater. Test temperature: _____
- Transfer test refrigerant to test tank
- Hang the refrigerant tank on the load cell
- Connect pressure transducer to tank outlet
- Fill each bubbler with 50 mL of DISTILLED water
- Bubbler lines connected
- Label sample bottles for transferring the bubbler solutions after the test
- Marquee in place
- Top off liquid N2
- SAFETY: Building 11 staff aware of testing
- Spot check all radiometers and thermocouples
- Span calibrate oxygen sensors
- DAQ – all instrument values nominal
- Set three ignition sources

Test Setup:

- RTO set to Normal Mode for ADD laboratory
- Discharge system vacuumed out (98% vacuum or better)
- Connect the tank to the discharge system via the refrigerant hose

- Charge system
- Note settled weight of tank assembly (hanging hose, heater, etc). Weight: _____kg
- System pressure stabilized to test pressure
- SAFETY valve is OPEN
- Discharge system manual valves OPEN
- Manual valve near discharge nozzle CLOSED
- Start bubbler pump. Adjust flow to 1 SCFH (0.5 L/min) on each.
- Start circulating water flow to the heat flux gauges
- Check positioning and focus of cameras
- Confirm bubblers through cameras
- Check diffuser setup
- Check electric match
- Open test room and hallway manual valves
- FTIR alignment OK
- FTIR Background
- Check TEST START function
- SAFETY: Locate all staff outside the test lab
- Set NI system to CONTINUOUS
- Enable camera recording
- Begin recording NI

Test

- SAFETY: Set DO NOT ENTER signage and strobe on lab door
- Vacuum release set to "TEST"
- TEST START T= 0 mins
- End of Background at T = 5 mins
- Discharge at T = 5 min
- End Discharge at T = 14 min
- Ignition at T = 14 min and 10 seconds
- Switch RTO to EXHAUST MODE at T = 34 mins

Post Test

- Relieve bubbler vacuum
- SAFETY: Allow HF background to return to normal before entering lab
- Transfer the contents of each bubbler to the labeled sample bottles.
- Backflush each 12ft sampling line with 50 mL of _____ and collect in BOTTLE 1 sample

Appendix E Scenario 1 – Ion Selective Electrode Measurements

Measurement Procedure

A two-part analysis process was used to detect the presence of hydrogen fluoride (HF) or hydrogen iodide (HI) in the combustion byproducts of each test in Scenario 1. The first part of the analysis was sample collection. This was done by extracting a sample from the collection hood and flowing this sample through two consecutive bubblers, as illustrated in Figure E-1. Samples were extracted at 0.5 L/min. Each bubbler was filled with 50 mL or 75 mL of distilled water; 75 mL for the tests requiring iodide measurement and 50 mL for the rest of the tests. Following the test, the sampling line between the probe and bubblers was rinsed with 50 mL or 75 mL of distilled water to collect any fluoride or iodide that remained in the line.

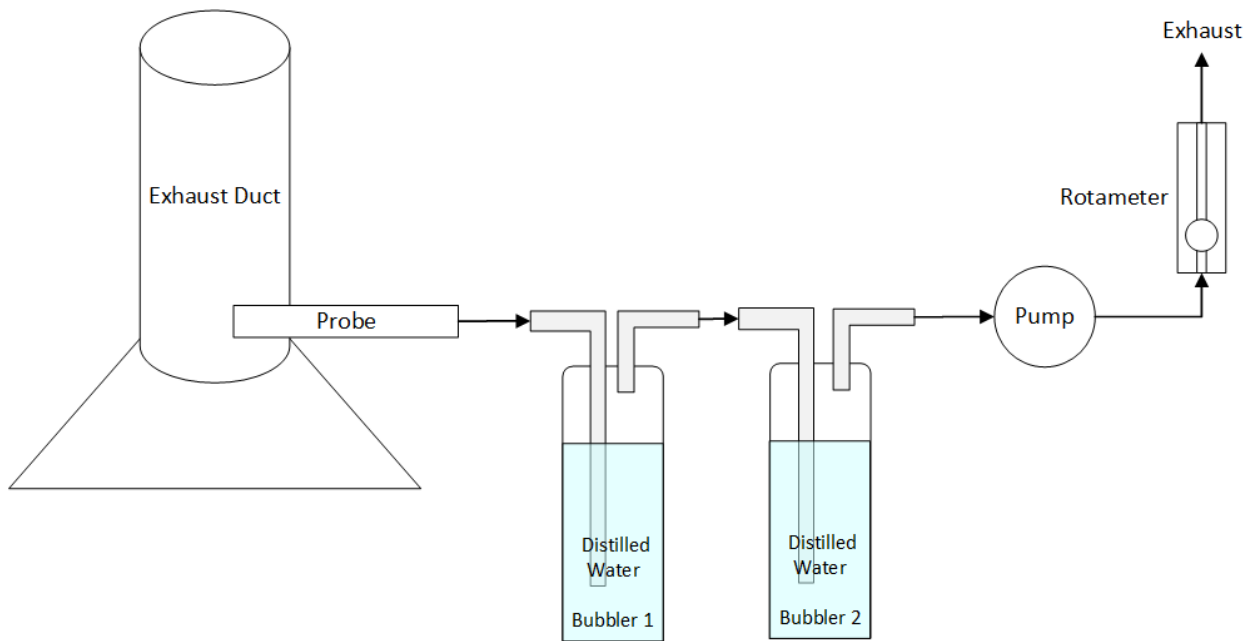


Figure E-1 - Sample Collection Setup

After the samples were collected, each was prepared for measurement using an ionic strength adjuster. Once prepared, the samples were measured with ion selective electrodes (ISE) for fluoride and iodide, with model numbers listed in Table E-1. All measurements were repeated three times and averaged.

Table E-1 – Fluoride and iodide measurement instrumentation

Measurement	Technique	Instrument
Fluoride concentration	Ion selective electrode	Thermo Scientific Orion fluoride combination electrode 9609BNWP
Iodide concentration	Ion selective electrode	Thermo Scientific Orion iodide combination electrode 9653BNWP
Ion selective electrode voltage	N/A	Thermo Scientific Orion Star A214 meter

Assumptions

All concentrations are reported as time-weighted averages normalized by the duration of refrigerant release in each test. It is assumed that all fluoride or iodide present in solution are extracted from HF or HI without any other halogen-containing compounds.

Calculation

Average concentration in the collection hood was calculated from ISE measurements using the following equation:

$$C_{ppmvol} = \frac{ISE_{ppmwt} * V_{sol} * \rho_{sol} * MW_{HydrogenHalide}}{V_{Gas} * MW_{Halogen} * \rho_{HydrogenHalide}}$$

The following values were used in the above equation:

Variable	Unit	Value for Fluoride	Value for Iodide
Average concentration in hood (C_{ppmvol})	ppm by volume	Calculated	Calculated
Concentration measured by ISE (ISE_{ppmwt})	ppm by mass	Measured	Measured
Volume of distilled water solution (V_{sol})	L	0.05 or 0.075	0.075
Volume of bubbled gas (V_{Gas})	L	0.5 L/min * Release Duration	
Density of distilled water solution (ρ_{sol})	g/L	1000	1000
Density of molecule at 25°C ($\rho_{HydrogenHalide}$)	g/L	0.818	5.228
($MW_{HydrogenHalide}$)	g/mol	20.0	127.9
($MW_{Halogen}$)	g/mol	19.0	126.9



Results

Uncertainty

Uncertainty calculations were conducted for each measurement with the following assumptions:

- Solution volume ± 2 mL
- Release duration ± 5 s
- ISE measurement ± 0.01 ppm by weight
- Bubbler flow rate ± 0.1 L/min

Based on this information, the measurements and uncertainties are shown in Table E-2 and Table E-3. The sum of individual uncertainties was applied to the measurement for time weighted average concentration. On average, the uncertainty in each measurement is 20% (k=1).

Table E-2 – Hood concentration measurements for HF

Test	Release Duration (s)	Average (ppm v/v)
S1-01	139	58 \pm 13.2
S1-02	240	32 \pm 7.0
S1-03	361	24 \pm 5.5
S1-04	140	33 \pm 8.0
S1-05	301	4 \pm 1.3
S1-06	240	37 \pm 8.0
S1-07	300	42 \pm 9.2
S1-08	300	36 \pm 8.0
S1-09	360	43 \pm 9.3
S1-10	140	156 \pm 33.6
S1-11	300	47 \pm 10.1
S1-12	140	177 \pm 38.0
S1-13	300	97 \pm 20.3
S1-14	300	121 \pm 25.3



Table E-3 – Hood concentration measurements for HI

Test	Release Duration (s)	Average (ppm v/v)
S1-08	300	1 ± 0.3
S1-12	140	7 ± 1.6

Other Uncertainty Factors

HF gas can react with water vapor within the combustion byproducts, then condense and be deposited on surfaces such as the collection hood, floor and walls. The quantity of HF deposited on surfaces and lost from the stream of combustion byproducts prior to arriving at the sample probe location(s) is unknown. This may result in measured values to be under reported. Quantifying the uncertainty with an upper bound is speculative without more knowledge about the extent of refrigerant combustion (partial or full combustion of the released refrigerant) and the resulting expected levels of HF generated.

Appendix F Scenarios 2-5 Ion Selective Electrode Measurements

Measurement Procedure

A two-part analysis process was used to detect the presence of hydrogen fluoride (HF) in the combustion byproducts of each test in Scenario 2-5. The first part of the analysis was sample collection. This was done by extracting a sample from the collection hood and flowing this sample through two consecutive bubblers, as illustrated in Figure E-1. Samples were extracted at 0.5 L/min. Each bubbler was filled with 50 mL.

Following the test, the sampling line between the probe and bubblers was rinsed with 50 mL of ionic strength adjuster into the same sample as the first bubbler. By preparing the sample in this way, the measurements for the first bubbler and the sampling lines are measured in combination. The resultant sample has an equivalent preparation for measurement as those collected and prepared in Scenario 1.

The sample collected from the second bubbler was prepared for measurement using an ionic strength adjuster.

For surface wipe samples, cotton swabs (Kimtech Science™ Kimwipes™) were dampened with distilled water and wiped across surfaces of interest. The swaps were then mixed with 50 mL of distilled water and 50 mL of ionic strength adjuster to prepare the sample for measurement.

Once prepared, the samples were measured with ion selective electrodes (ISE) for fluoride, with model numbers listed in Table F-1. All measurements were repeated three times.

Table F-1 – Fluoride and iodide measurement instrumentation

Measurement	Technique	Instrument
Fluoride concentration	Ion selective electrode	Thermo Scientific Orion fluoride combination electrode 9609BNWP
Ion selective electrode voltage	N/A	Thermo Scientific Orion Star A214 meter

Assumptions

All concentrations are reported as time-weighted averages normalized by the duration of refrigerant release in each test. It is assumed that all fluoride or iodide present in solution are extracted from HF without any other halogen-containing compounds.

Calculation

Average concentration in the collection hood was calculated from ISE measurements using the following equation:

$$C_{ppmv} = \frac{ISE_{ppmw} * V_{sol} * \rho_{sol} * MW_{HydrogenHalide}}{V_{Gas} * MW_{Halogen} * \rho_{HydrogenHalide}}$$



The following values were used in the above equation:

Variable	Unit	Value for Fluoride
Average concentration in duct (C_{ppmvol})	ppm by volume	Calculated
Concentration measured by ISE (ISE_{ppmwt})	ppm by mass	Measured
Volume of distilled water solution (V_{sol})	L	0.050 or 0.075
Volume of bubbled gas (V_{Gas})	L	0.5 L/min * Release Duration
Density of distilled water solution (ρ_{sol})	g/L	1000
Density of molecule at 25°C ($\rho_{HydrogenHalide}$)	g/L	0.818
($MW_{HydrogenHalide}$)	g/mol	20.0
($MW_{Halogen}$)	g/mol	19.0

Uncertainty

On average, the uncertainty in each measurement is 20%, as mentioned in Appendix E.

Other Uncertainty Factors

HF gas can react with water vapor within the combustion byproducts, then condense and be deposited on surfaces such as the collection hood, floor and walls. The quantity of HF deposited on surfaces and lost from the stream of combustion byproducts prior to arriving at the sample probe location(s) is unknown. This may result in measured values to be under reported. Quantifying the uncertainty with an upper bound is speculative without more knowledge about the extent of refrigerant combustion (partial or full combustion of the released refrigerant) and the resulting expected levels of HF generated.

Appendix G Hydrogen Fluoride (HF) and Hydrogen Iodide (HI) Exposure Hazards

The following reference information is provided to firefighters for their consideration and development of additional tactics to improve outcomes for firefighters and the public they serve.

Typical safety data sheets for hydrogen fluoride (HF) includes the following information [8]:

- Eye Contact: Causes serious eye damage
- Inhalation: Toxic if inhaled
- Skin contact: Causes severe burns

Below is a list of exposure limits for HF gas:

ACGIH® TLV (United States, 3/2017).

- Absorbed through skin. Notes: as F
- Ceiling: 2 ppm, (as F)
- TWA: 0.5 ppm, (as F) 8 hours.

NIOSH REL (United States, 10/2016). Notes: as F

- Ceiling: 5 mg/m³, (Fluoride as F) 15 minutes.
- Ceiling: 6 ppm, (Fluoride as F) 15 minutes.
- TWA: 2.5 mg/m³, (Fluorides as F) 10 hours.
- TWA: 3 ppm, (HF as F) 10 hours.

OSHA PEL (United States, 6/2016). Notes: as F TWA: 2.5 mg/m³, (as F) 8 hours.

OSHA PEL 1989 (United States, 3/1989). Notes: as F

- STEL: 6 ppm, (as F) 15 minutes. TWA: 3 ppm, (as F) 8 hours.

OSHA PEL Z2 (United States, 2/2013). TWA: 3 ppm 8 hours.

Exposure hazards for hydrogen iodide gas are similar to HF.

Cho et al. [9] report the acute symptoms of a large spill accident of HF. While this may not be applicable to firefighters involved in a residential compartment fire, the conclusions are quoted here.

“The subjects who worked near the site of the hydrogen fluoride spill, worked for an extended period, or worked without wearing respiratory protective devices more frequently experienced upper/lower respiratory, gastrointestinal, and neurological symptoms. Further follow-up examination is needed for the workers who were exposed to hydrogen fluoride during their collection duties in the chemical plant in Gumi City.”

The EPA has published Acute Exposure Guideline Levels (AEGL) shown in the following table [10].

TABLE 3-1 Summary Table of AEGL Values (ppm [mg/m³])

Classification	10 min	30 min	1 h	4 h	8 h	End Point (Reference)
AEGL-1 (Nondisabling)	1.0 (0.8)	1.0 (0.8)	1.0 (0.8)	1.0 (0.8)	1.0 (0.8)	Threshold, pulmonary inflammation in humans (Lund et al. 1997, 1999)
AEGL-2 (Disabling)	95 (78)	34 (28)	24 (20)	12 (9.8)	12 (9.8)	NOAEL for lung effects in cannulated rats (Dalbey 1996; Dalbey et al. 1998a); ^a sensory irritation in dogs (Rosenholtz et al. 1963) ^b
AEGL-3 (Lethal)	170 (139)	62 (51)	44 (36)	22 (18)	22 (18)	Lethality threshold in cannulated rats (Dalbey 1996; Dalbey et al. 1998a); ^c lethality threshold in mice (Wohlschlagel et al. 1976) ^d

^a10-min AEGL-2 value.

^b30-min and 1-, 4-, and 8-h AEGL-2 values.

^c10-min AEGL-3 value.

^d30-min and 1-, 4-, and 8-h AEGL-3 values.




Abbreviations: mg/m³, milligrams per cubic meter; ppm, parts per million.

Appendix H Comparing Heat Release Rates and Heat Fluxes

Heat Release Rates

Heat release rate is a measure of the energy generated by a burning fuel package. The heat release rate is used to understand how the energy released from that fuel would change the thermal conditions in a room or how it might ignite other nearby fuels via heat transfer.

Table H-1 – Examples of Heat Release Rates

Peak Heat Release Rate	Fuel Package	Before	At Peak Heat Release Rate
80 Watts	Candle		
50 kW	Plastic waste container with small wax cups		

Peak Heat Release Rate	Fuel Package	Before	At Peak Heat Release Rate
150 kW to 300 kW	30 gallon trash container with construction debris ¹		
2,000 kW	Upholstered Chair		
4,000 kW	Overstuffed Sofa		
7,000 kW	12 ft by ft 12 Living Room with adequate ventilation		

¹ https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=861237



Heat Flux

Heat Flux is the rate of heat energy transferred per unit surface area. Typically measured in kW/m².

Table H-2 – Examples of Heat Flux

Heat Flux (kW/m ²)	Comparison
1	Thermal radiant heat from the sun (cloudless sky)
3 to 5	Heat flux that will cause pain to human skin within seconds
20	Heat flux at the floor (8 ft ceiling height) during flame rollover/beginning of flashover
84	Heat flux exposure during Thermal Protective Performance (TPP) test for Firefighter Turnout Gear
60 to 200	Range of heat flux during flame impingement on a surface

High heat flux levels can cause second degree burns to exposed skin in just seconds as shown in Figure H-1.²

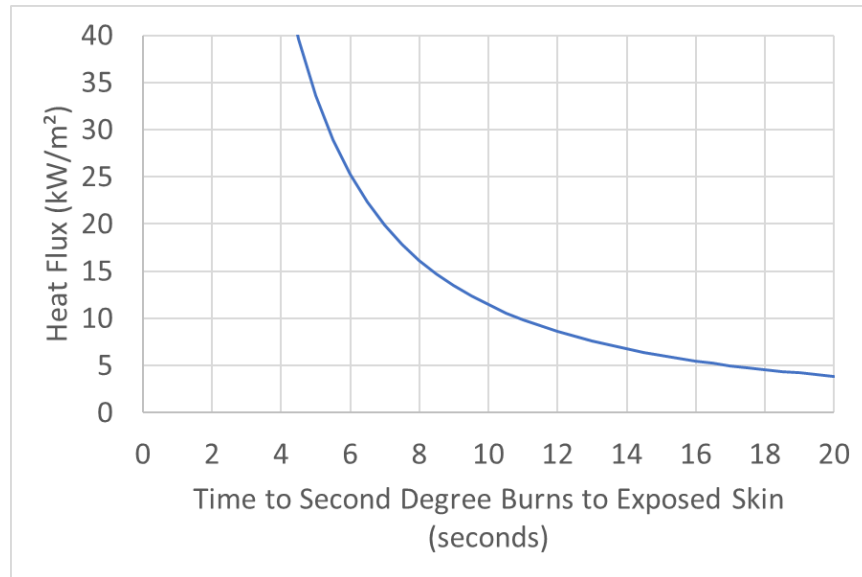


Figure H-1 – Heat Flux Levels and Time of Exposure to cause 2nd degree burns.

² ISO 13571, "Life-threatening components of fire — Guidelines for the estimation of time to compromised tenability in fires", 2nd Ed., 2012

