Air-Conditioning, Heating and Refrigeration Technology Institute

Final Report

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BENCHMARKING RISK BY WHOLE ROOM SCALE LEAKS AND IGNITIONS TESTING OF A2L REFRIGERANTS

Final Report

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DISCLAIMER

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- Air-Conditioning, Heating and Refrigeration Institute (AHRI)

Preface by AHRTI Project Monitoring Subcommittee

This research project started in late June of 2016. The CFD work was completed in July and whole room main effects design of experiments or referred to as "calibration tests" Task 1 began in August. Equipment testing, Task 2, began in October and was completed on December 9th. This was a large project and it proceeded at a fast pace.

One decision made initially was to always use ignition sources that were thought to have sufficient energy to cause ignition if a flammable mixture reached the ignition source. The reason for this was that the PMS was interested in learning about the severity of post ignition events, if ignitions did occur. Likewise, ignition sources were placed in locations where we judged combustible mixtures were most likely to occur. Because of the way we approached these experiments, some relatively low probability events were forced to occur and we have learned some things that were not previously known to us (a few insights are listed below). For the majority of Task 1 tests, the refrigerant charge quantity released corresponded to 50% of the lower flammability limit (LFL) when fully mixed into the entire room volume, regardless of release height or rate. The 50% of LFL value was selected based on a number of draft standards potentially allowing up to or greater than a 50% LFL equivalent refrigerant discharge into a room for a high wall (1.8 meter) leak event. It should be noted that several of the tests would actually be outside of the proposed standards, i.e. more refrigerant was leaked into the space without the mitigation proposed by the standard. Four tests were run at 25% LFL at the lowest release height (0.2 meters) to determine the main effects of reducing refrigerant concentration and refrigerant type. The PMS feels that follow-up research projects will be needed to enable us to provide the best guidance to the developers of HVAC&R safety standards and building codes. Future work should include reviewing irregular test results, and potentially include updating risk assessments to better quantify both the probability of occurrence and severity of any ignition events, with a more thorough evaluation of:

- the probabilistic distribution of real world ignition sources in terms of ignition energy, quantity, spatial location throughout the room, and activation frequency
- the probabilistic distribution of different refrigerant release scenarios, across a range of leak rates and total refrigerant charge released

Learnings:

- In Task 1, liquid refrigerant releases do not fully vaporize at the release valve or orifice and refrigerant liquid remained after the refrigerant release completed, either as droplets, pooled liquid on floor, or liquid running down the wall adjacent to the leak, or all three in combination. Refrigerant liquid could be seen on the floor even after a flammable event had self-extinguished and high temperatures were seen in the room. In addition, thermocouples recorded low temperatures near the atmospheric boiling points of the refrigerants just adjacent to where the refrigerant was being released, also indicating the presence of liquid refrigerant being sprayed onto the thermocouples, potentially as droplets.

- Depending upon the operating state of the equipment and the location of the leakage point within the refrigerant circuit, the release may be mainly vapor or a vapor/liquid mixture. The

CFD studies that have been used to guide the industry do not consider the possibility of a mechanism that can pool liquid refrigerant at the floor or droplet formation suspended in the air (refrigerant fog). This, of course, significantly changes the refrigerant concentration regime. Further work done by Robert Uselton at Lennox laboratories with R-410A liquid refrigerant leaks similar to what was done in this work confirmed refrigerant liquid could remain for hours depending on the leak methodology. Further work would be warranted to understand the two-phase and time factor dynamics of various liquid refrigerants leaks scenarios. CFD models would need to be updated to accurately reflect the correct release phenomena. Product risk assessments would also need to be reassessed with this new information. [Also see ASHRAE RP-1448 final report for discussion of relevant leak scenarios including pooling of liquid on the floor.]

- In many refrigerant releases in Task 1, a fog was seen forming in the room during the release. It was originally assumed that this was water moisture condensing as the refrigerant cooled the air. However, in later Task 2 experiments, it became apparent that this could be refrigerant fog and not a water moisture induced fog. In Task 2, many two-phase liquid/vapor refrigerant releases occurred into a compartment first before being introduced into the room which allowed the refrigerant to absorb some heat. In these cases, when the refrigerant was then released into a room that had the same elevated temperature and humidity conditions as Task 1, no fog was formed. This would indicate that reduced air temperature may not be the driver for the fog formation.

- The low burning velocity of 2L refrigerants does not prevent rapid flame spread under many conditions we observed. Moreover, ignitions can occur even when the local air velocity is much higher than the laminar burning velocity. This observation may require further investigation as it may be related to ignition source energies used.

- For some classes of refrigeration equipment (reach-in coolers, walk-in coolers, etc.) medium or large leaks can cause refrigerant accumulation in the cold storage compartment. Since these 2L refrigerants are heavier than air, flammable concentrations can be reached fairly easily in such confined spaces. When a door is opened, there is a spill of refrigerant to floor level leading to possible ignition.

- Cursory evaluation of hazard mitigation systems suggests refrigerant detection systems will need to have a faster response time than the 30 second response time that had been originally envisioned. More investigation is needed.

- Some of the applications evaluated looked good for typical “nominal” refrigerant charges. Larger charges, up to the maximum allowed by guidance of current draft standards, were not necessarily validated with data and could well present a greater hazard.

Acknowledgement

UL LLC appreciates the direction, guidance, and contributions of AHRTI's Project Management Subcommittee (PMS). The members of the committee include the following:

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UL Executive Summary

The phase-out 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 the equipment that uses them. Several Class A2L refrigerants have been identified as potential replacement for refrigerants currently used in HVAC and refrigeration systems. Safety evaluation of these Class A2L refrigerants requires an understanding of refrigerant flammability in representative-scale settings so that equipment can be appropriately designed and installed for safe operation.

The objective of this research is to conduct refrigerant leak and ignition testing under whole room scale conditions to develop data and insight into the risks associated with the use of Class A2L refrigerants versus the Class 1 refrigerants currently in use while considering ambient conditions (temperature and humidity) and refrigerant lubricants.

A technical plan was developed that included investigation of refrigerant concentrations in room-scale experiments. Calibration experiments developed data on the influence of refrigerant charge, leak rates, leak locations, and leak opening size on the accumulation of refrigerant concentration and the potential for ignition. Parametric test experiments investigated the influence of ambient temperature and humidity, obstructions representing furniture within the test room, lubricating oil, and refrigerant leak quantity on potential for ignition. Tests were also conducted in larger-scale scenarios to investigate potential for ignition and fire hazard in representative residential and commercial installations. All experiments were performed in a nominal 30 x 30 x 8 ft. (9.1 x 9.1 x 2.4 m) [L x W x H] chamber that provided a controlled temperature and humidity test environment. The test chamber was designed to contain the released refrigerants and combustion products which were then processed through UL's smoke abatement system.

Prior Research Review and UL CFD Simulations

A review of previous research on Class A2L refrigerants provided a reference for this investigation relative to measurements, refrigerant release methods, and refrigerant build-up in different scenarios. The literature review identified a need for additional CFD (Computational Fluid Dynamics) simulations to develop insights into refrigerant build-up from leaks into a test room, safety of the laboratory operations, and placement of instrumentation and ignition sources. The CFD simulations performed were based on a refrigerant quantity equal to 50% of the LFL concentration if uniformly mixed in the room. A total of eight simulations were performed with each combination of leak locations, mass flow rate, and leak opening size. The findings from the UL CFD simulations were as follows:

a) Refrigerant release at a higher velocity (100 g/s through 50 mm opening) from 2.2m height results in a jet that mixes with the ambient air. The resulting refrigerant concentration in the test room is below the lower flammability limit (LFL) except in a narrow region surrounding the jet flow. However, if refrigerant is released from a lower level at the same velocity, obstructions impede jet flow mixing in the room volume and create flammable mixtures at the floor level.
b) Refrigerant release at lower velocity (13.5 g/s through a 300 mm opening) from 2.2 m height allows the refrigerant to continually mix with the air. Only a relatively small volume of

flammable mixture develops near the release location. However, refrigerant released from a lower level (0.2 m) at the same velocity, generally results in pooling flammable refrigerant-air mixtures.

c) Based upon the CFD simulations and analysis of refrigerant concentrations, the results show an area in between the obstruction and release opening provides a suitable location for ignition of refrigerant-air mixtures.

Hazard Controls

The conduct of this fire 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, acid gases (particularly hydrogen fluoride gas and hydrogen fluoride acid), electric shock, frostbite, and mechanical hazards. Potential hazards to the environment included releases of refrigerant gases, decomposition products and combustion products that were expected to be toxic and corrosive. Hazards were addressed through design of the test facility and through procedures that included (1) Elimination, (2) Engineering controls, (3) Administrative controls, and (4) Personal protective equipment.

Calibration Tests

The calibration tests were conducted in a 2.4m x 3.6m x 2.4m high test room to determine the influence of leakage rate, leakage location, opening size, and temperature and humidity. The results from these tests assisted in selection of test conditions for the parametric and scenario tests. The findings from calibration tests were as follows:

1. Refrigerant release rate, release height and refrigerant line opening size influence mixing or pooling of the refrigerant in the test room.
2. The mixing of the refrigerant is influenced by obstructions (e.g., furniture) such that a high velocity jet does not fully mix with air and develops a local area of flammable mixture.
3. Low release velocity flows (low release rate of 13.5g/s, 356 mm opening with baffling) at 0.2 m release height resulted in pooling of the refrigerant with concentrations near the floor level higher than the upper flammability limits. In these cases, ignition occurred only after the concentration decreased below the UFL from diffusion mixing process.
4. High release velocity flows (high release rate of 100g/s, 25 mm opening) at the 2.2 m release height resulted in turbulent mixing of the jet with air. Subsequently, refrigerant concentrations were below their lower flammability limit. This test did not result in ignition. In this case, the obstruction did not influence the jet as it was below the mixing zone.
5. All but one test in the calibration series were conducted with R-32 refrigerant. Several of these tests resulted in ignitions. One test was conducted with R-452B (high release rate of 100 g/s; 25 mm opening, at 0.2 m release height) which resulted in ignition.
6. An intermediate mass release rate (55 g/s in Cal13) through the 356 mm opening with baffling at the 2.2 m release height resulted in the observation of liquid refrigerant pooling on the floor and a significant fire event. Cal17 was similar to Cal13 but at the 1.8 m release height. Liquid refrigerant was also observed pooling on the floor.

Parametric Tests

Parametric tests were conducted in a 2.4m x 3.6m x 2.4m high test room to investigate influence of ambient temperature and humidity, obstruction, refrigerant leak quantity, and lubricating oil on potential for and severity of ignition. In these tests, the leakage location was at 0.2m height location, the leakage rate was 100 g/s, and delivered through a 25 mm size opening. The findings from the parametric tests are as follows:

1. Refrigerants R-22 and R-410A with lubricating oil (1.5 and 3.0%) did not ignite under the test conditions used in this investigation.
2. Ignition of R-32 in higher ambient temperature and humidity conditions (91 °F and 70 % RH) resulted in higher maximum pressure in the test room, and longer duration fire for R-32 refrigerant.
3. Ignition of R-452B in lower temperature and humidity conditions (73 °F and 50 % RH) resulted in higher maximum temperature in the test room, but the duration of flaming was longer. Ignition of R-452B at 91°F and 70% RH resulted in a higher pressure rise.
4. The presence of the obstruction in the room increases mixing of the refrigerant release with room air and develops local conditions that have a flammable refrigerant mixture that is above the LFL and conducive to ignition. The volume of the obstruction was not used to reduce the volume of the room in calculating the planned refrigerant discharge amount. Without the obstruction, ignition did not occur for either R-32 or R-452B refrigerant.
5. In general, reducing the refrigerant quantity to achieve an average room concentration equal to 25% LFL, and with obstruction, reduced the fire size and temperatures observed in the room. Further, the fire was localized to the area of the ignition source.
6. R-452B tests with lubricating oil (1.5 and 3.0%) and no obstruction did not result in ignition. R-452B refrigerant tested without lubricating oil and with no obstruction did result in ignition.
7. R-32 refrigerant ignited with a significant fire with 1.5% lubricating oil and no obstruction, but had a relatively small fire with 3.0% lubricating oil.

Scenario Tests

Room scale tests were performed for commercial and residential scenarios. The commercial scenarios included (i) Packaged Terminal Air Conditioner (PTAC) unit in a motel room; (ii) Rooftop unit in commercial kitchen; (iii) Walk-in cooler; and (iv) Reach-in refrigerator in a convenience store. Residential scenarios included (v) Split HVAC unit with evaporator section in a utility closet; (vi) Split HVAC unit servicing error; and (iii) Split HVAC unit Hermetic Electrical Pass-Through Terminal failure. Each scenario was developed based upon input from the AHRTI Project Management Subcommittee (PMS).

Throughout this report, refrigerant charge amounts were calculated based on proposed changes to the appropriate standards or based on expert judgment of the PMS. For some scenarios, the refrigerant charge amounts were based on m_1 per proposed draft IEC 60335-2-40. Refrigerant charges related to m_1 are not based on room volume or floor area as m_1 is considered safe without restrictions. In this report, room volumes and percentage of LFL are provided so that comparisons may be made to other standards which use Refrigerant Concentration Limit (RCL). Typically, RCL values are 25% or 20% of LFL.

The findings from each of the scenarios are presented herein.

PTAC Unit in Motel room

The PTAC tests were designed to emulate the release of refrigerant from the evaporator into a typical motel room with ignition devices representing those sources that could be expected to occur. The refrigerant quantity released in the tests corresponds to proposed m_1 size charge of $(6\ m^3 \times LFL\ \frac{kg}{m^3})$, where LFL is the lower flammable limit in kg/m³ from for the refrigerant used (as proposed for future edition of IEC 60335-2-40 in subclause GG.1.1 and future adoption in North America). For the typical motel room size selected for this project (1660 ft³, 47.1 m³), this quantity of refrigerant is equivalent to an average concentration that is approximately 13% of the LFL if the refrigerant is completely mixed in the test room volume. Nine tests were conducted for this scenario using R-32 and R-452B refrigerants. The ignition sources were tea candles (open flame) placed at floor level or electric arc sources which continually arced once energized at the various locations. In some of the tests, the candle ignition source failed to either ignite or stay ignited. Refrigerant concentrations measured in the test room did not show values above the LFL and ignition did not occur. One test using R-452B resulted in a low energy ignition near the PTAC power cord plug lasting no more 3 seconds. There was no secondary ignition of the cheesecloth for either refrigerant in this test. An additional test was added placing the electric arcs directly in front of the PTAC in the refrigerant discharge zone. This test resulted in ignition of the refrigerant.

Rooftop Unit in Commercial Kitchen

The commercial kitchen scenario involved the use of a roof top unit with duct work connected to the kitchen space below. The kitchen size was 14 x 16 x 8 ft. high (4.3m x 4.9m x 2.4m). The release quantities for R-32 and R-452B were based on a IEC SC 61D Working Group 9 draft version of IEC 60335-2-40 (Annex GG section: GG.10.1). Five tests were conducted for this scenario using R-32 and R-452B refrigerants. Tests represented a refrigerant leak in the evaporator in the air handler. This location was approximately 9 ft. (2.7m) above the work surfaces. In these tests, the HVAC unit fan was turned on 30s or 60s after the start of refrigerant release as a mitigation technique. There was accumulation of the leaked refrigerant in the evaporator condensate drain pan and therefore not all the refrigerant entered the test room. This resulted in lower concentrations of refrigerants and no ignition was observed. In these tests, the candle ignition source was extinguished by the fan-induced flow of the air-refrigerant mixture in the test room.

Walk-in Cooler

The walk-in cooler scenario involved the use of a ceiling mounted commercial refrigeration unit with the refrigerant leak in the evaporator. The refrigerant release quantities were based on $13\ m^3 \times LFL\ \frac{kg}{m^3}$ (from draft version of IEC 60335-2-89) for R-455A and R-457A. Seven tests were conducted for this scenario using R-455A and R-457A refrigerants. The location of the discharge had a significant effect on ignition results. Tests with the discharge at the return bend of the evaporator in the unit cooler forced the refrigerant to leave the unit cooler through the condensate drain and drop to the floor. This direct path to floor level (approximately 7 ft., 2.1m) resulted in flammable refrigerant mixtures. In contrast, the discharge through the coil face resulted in turbulent mixing of the refrigerant with air before the cooled mixture dropped to floor. This indirect path to floor level resulted in greater mixing of the refrigerant with room air. There was no ignition of the refrigerant when the discharge was from the coil face due to turbulent mixing before the mixture dropped to the floor. The position of the test room door, open or closed, appeared to have little impact on ignition results.

Reach-in Cooler

The reach-in cooler scenario involved a product display refrigerator having an internal volume of 21 ft^3 (0.59 m^3), located in a convenience store with dimensions of 30 x 30 x 8-ft. high (9.1m x 9.1m x 2.4m). Tests with release quantities of 300g, 400g, and 500g were performed. The 500 g value is the current limit for class 2 flammable refrigerant in UL 471 edition 10 including revisions through November 2014. Four tests were conducted for this scenario using R-455A and R-457A refrigerants. The reach-in cooler tests showed that ignition of the refrigerant occurs with a refrigerant release quantity greater than 300g. The fire spread indicated that walls and corners in proximity of the reach-in cooler facilitate higher concentrations of refrigerants.

In those cases where ignition occurred, the highest temperatures attained were near the floor level. The 300 gram test showed some flaring of the candles due to the presence of refrigerant, but there was no visible spread of flame into the surrounding air. Maximum temperatures from the events increased with increasing charge size. Both 400 and 500 gram charge sizes resulted in ignition. R-455A had approximately 150 ^oF lower maximum temperatures than R-457A for the same release mass of 500 grams.

Split HVAC unit in a utility closet – Internal Leak

The residential A/C application test scenario involved a HVAC unit located in a 24ft. 2in. x 30ft. x 8ft. (7.4 x 9.1 x 2.4m) residential arrangement with the air conditioning unit located in an 8 x 4 x 8-ft. (2.4 x 1.2 x 2.4m) closet. The refrigerant release quantity was based upon a proposed revision to IEC 60335-2-40. The value of 6 $m^3 \times LFL\ \frac{kg}{m^3}$was used for the test cases without mitigation (m_1 charge). In this scenario, five tests were performed with internal leak in the A-coil area using R-32 and R-452B refrigerants. Tests were also conducted with a proposed IEC 60335-2-40 WG9 mitigation procedure using the HVAC unit fan to circulate the leaked refrigerant, with the fan energized 30s after initiation of refrigerant release.

In the tests with and without mitigation, the both R-32 and R-452B refrigerants ignited in the hallway in less than 12s in proximity to the return grill where pilot flame and electric arc sources were located. While most of the flaming occurred in proximity of the leaked refrigerants near the return grill, there was some spread of flame along the hallway.

The mitigation procedure appeared to reduce the time for flaming in the hallway. However, the flames were drawn into the HVAC unit through the return grill and flaming was observed within the unit. Smoke was observed emitting from the supply grill as the flames were drawn into the return grill. Without mitigation, the flaming was of longer duration by approximately 40s in the hallway even though the refrigerant charge released was less.

Comparing the leakage rates between the A-coil leak and servicing error tests, the leakage rate was higher in the A-coil test (using a constant flow rate) compared to the natural pressure decay used in the servicing error test.

Split HVAC unit in a utility closet – Servicing Error

The residential A/C application test scenario involved a HVAC unit located in a 24ft 2in x 30ft x 8ft (7.4 x 9.1 x 2.4m) residential arrangement with the air conditioning unit located in a 8 x 4 x 8 ft. (2.4 x 1.2 x 2.4m) closet. In this scenario, three tests were conducted using R-410A, R-32 and R-452B refrigerants. The refrigerant charge used was the same as that used in the A-coil experiments. However, the refrigerant was released under natural pressure decay to represent a servicing scenario such as a mistake during joint brazing. In all of these scenarios 30g lubricating oil was mixed with each refrigerant prior to release.

Ignition was not observed with R-410A refrigerant. However, ignition occurred for both R-32 and R-452B refrigerants near the release location which was located inside the closet. There was no ignition of the refrigerant outside the utility closet for either refrigerant.

The candle ignition sources were placed near the point of release. Once the discharge started, these candles were immediately extinguished by the discharge. Ignition was observed once the electric arc was energized. The location of the electric arc and the discharge rate combined to limit the ignited volume to the immediate vicinity of the electric arc.

Hermetic Electrical Pass-Through Terminal Failure

The Hermetic Electrical Terminal failure scenario involved the use of the outdoor section of a residential compressor/condenser unit. Four tests were conducted for this scenario using R-32, R-452B, and R-410A refrigerants. Each test was conducted using a new factory-built compressor charged with refrigerant and lubricating oil. A 1/8 inch hole was drilled in the Hermetic Electrical Terminal plug to represent a terminal failure. The results from the Hermetic Electrical Terminal failure tests showed that R-452B ignited under these test conditions. In the R-452B experiment, it was observed that the molded plug remained attached to the terminal which was different from all other experiments where the molded plug was completely ejected. The experiment with R-410A was repeated because of concern about the seating of the terminal plug on the electrical terminals. In both R-410A tests, there was no ignition. It was anticipated that R-32 would ignite under these same conditions, but an electrical interference from the electric arc influenced the solenoid valve controlling the refrigerant discharge and caused reduction in the overall rate of R-32 discharge. This slower rate of the R-32 discharge resulted in refrigerant/air mixtures that were not ignitable.

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1. Benchmarking Risk by Whole Room Scale Leaks and Ignitions Testing of Refrigerants

1.1. Background

The phase-out 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. Research is being conducted by the refrigeration and air conditioning industry to develop lower Global Warming Potential (GWP) / zero Ozone Depletion Potential (ODP) alternatives. Class A2L refrigerants, made up of refrigerant blends or single component refrigerants which can contain olefinic and non-olefinic type refrigerant compounds, represent the most recent in the development of deployable reduced GWP/zero ODP refrigerants. Safety evaluation of these Class A2L refrigerants requires an understanding of refrigerant flammability in representative-scale settings so that equipment can be appropriately designed to maintain safe operation.

1.2. Objectives

The objective of this research is to conduct refrigerant leak and ignition testing in whole room scale scenarios to develop data and insight into the risk associated with the use of Class A2L refrigerants as opposed to the Class 1 refrigerants currently in use while considering ambient conditions (temperature and humidity) and refrigerant lubricants. The ignition sources chosen had sufficiently high energy (open flames or electrical arcs) to ignite A2L refrigerants and refrigerant-lubricants mixtures.

1.3. Scope

This research includes baseline evaluation of Class A1 refrigerants (e.g., R-410A and R-22), and four Class A2L refrigerants (R-32 and R-452B, or R-455A and R-457A) selected for each scenario equipment application type, each with appropriate lubricants. In addition, R-22 refrigerant with mineral oil lubricant is compared to R-410A with POE lubricant.

1.4. Technical Plan

The ignition sources used in this project were intentionally of high energy to insure likelihood of ignition when they are in the presence of a flammable mixture. The electric arc system was operated continuously and simultaneously in multiple locations in the test space. The experiments were conducted at near-full-scale and this type of ignition system was vital to provide a true signal of combustion potential taking into account factors that included the following:

- Ambient temperature and humidity
- Mixing of the refrigerant with air
- Refrigerants flammability, leakage rate, location, quantity, and opening size
- Lubricating Oil
- Obstructions

According to previous AHRI studies, the probability of a continuous high energy electrical arc occurring in a residential or light commercial conditioned space is low. Thus, the results are expected to provide the potential worst case severity of ignition events for the A2L refrigerants tested rather than the probability of occurrence.

The technical plan developed to meet the objective of this research included the following tasks.

Task 0 – Detailed Review of AHRI 8004, AHRI 8009 and AHRI 8016 Project Reports

Task 1 – Refrigerant Leak and Ignition Testing Under a Controlled Environment

Task 2 – Refrigerant Leak and Ignition Testing Under a Whole Room Scale

Task 3 – Data Analysis and Discussion

Task 4 – Technical Report

The project investigation plan is presented in Figure 1.

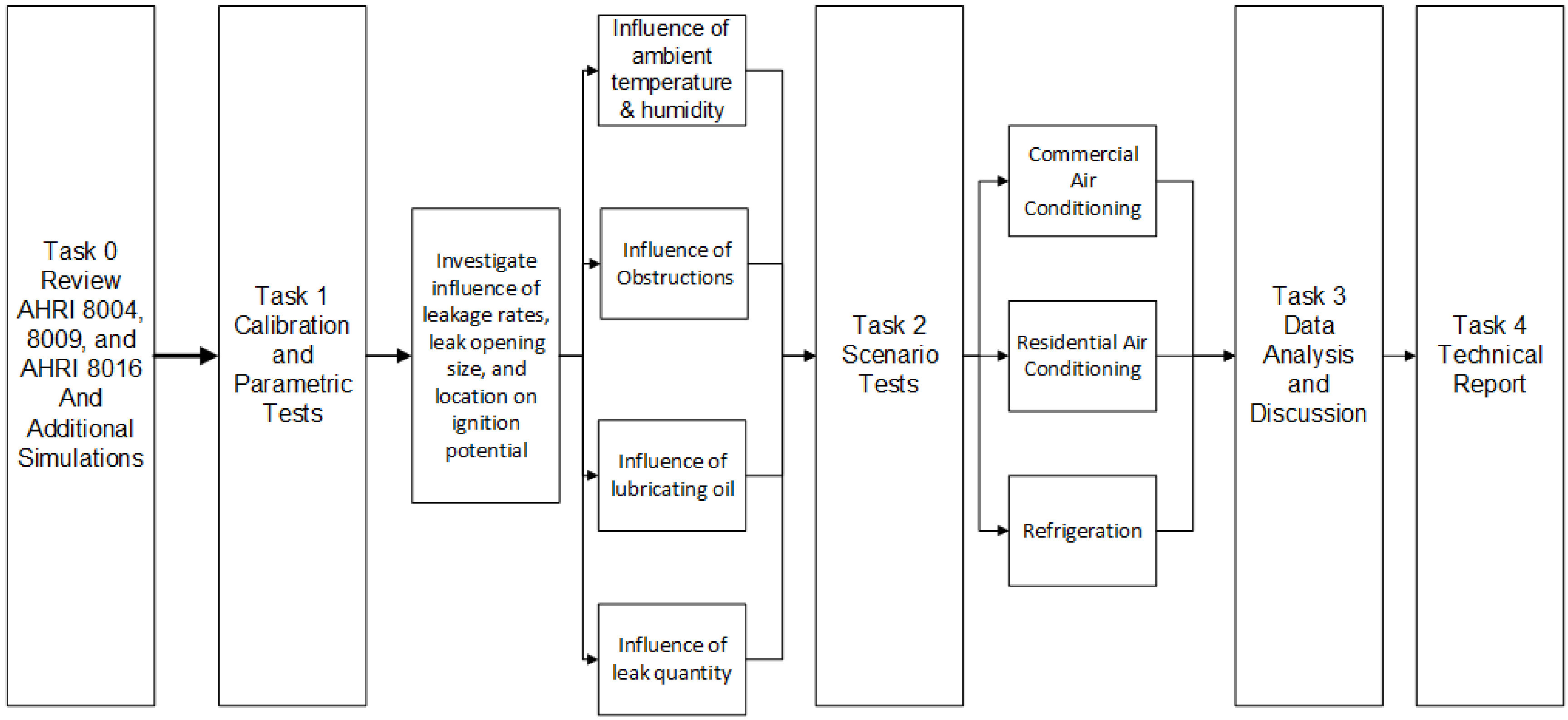


Figure 1 – Technical Plan

1.5. Refrigerants

Table 1 presents the properties of refrigerants used in this project (from ANSI/ASHRAE Standard 34-2016 and ISO 817:2014).

Table 1 – Refrigerant Release Properties and Quantities

Parameter	R-22	R-32	R-410A	R-452B	R-455A	R-457A
Lower Flammability Limit (LFL, % volume)	no flame propagation	14.4	no flame propagation	11.9	11.8	6.0
(LFL, kg/m³) Sea Level		0.307		0.310	0.423	0.215
(LFL, kg/m³) 200 m (650 feet)		0.301		0.304	0.415	0.211
Upper Flammability Limit (UFL, % volume)	no flame propagation	29.3	no flame propagation	22.0	12.9	18
Refrigerant Concentration Limit (RCL, ppm v/v)	59,000	36,000	130,000	30,000	22,000	15,000
Laminar Burning Velocity (cm/s)	no flame propagation	6.7	no flame propagation	<4.0	<1.5	6.3
Composition (% mass)	100% R-22	100% R-32	50% R-32 50% R-125	67% R-32 26% R-1234yf 7% R-125	75.5% R-1234yf 21.5% R-32 3.0% R-744	70% R-1234yf 18% R-32 12% R-152a

When converted to mass basis (kg/m³), the LFL values were adjusted for the test site elevation of 200 meters (650 feet).

2. Task 0 – Detailed Review of AHRI 8004, AHRI 8009 and AHRI 8016 Project Reports

Previous research included refrigerant dispersion simulations and experiments in residential [1] and commercial application scenarios [2] for several A2L refrigerants and subsequent risk analysis using fault trees analysis.

Building upon research by Goetzler et al.[3], AHRTI has identified key scenarios for refrigerant leakage that may result in refrigerant ignition (AHRI 8004) as shown in Table 2.

[1] Risk Assessment of Residential Heat Pump Systems Using 2L Flammable Refrigerants, AHRI Project 8004 Final Report, Air-conditioning, Heating and Refrigeration Institute.

[2] Risk Assessment of Refrigeration Systems Using A2L Refrigerants, AHRI Project 8009 Final Report, Air-conditioning, Heating and Refrigeration Institute.

[3] Goetzler, W; Bendixen, L; Bartholomew, P. 1998. "Risk Assessment of HFC-32 and HFC-32/134a (30/70 wt. %) in Split System Residential Heat Pumps, Final Report." Arthur D. Little, Report to Air Conditioning and Refrigeration Technology Institute, NTIS DE-98005596; DOE/CE/23810-92. 88p.

Table 2 – Refrigerant Leakage Scenarios Potentially Leading to Ignition

Row	Leak Scenario	Description
1	A leak occurring in a heat pump system while the unit is idle.	The leak could occur in either the inlet piping or the air handler and could be due to an improperly brazed joint or equipment fatigue. The system could be located in one of four possible locations – an attic, basement, garage, or utility closet – and in the event of a leak; the refrigerant could accumulate in these surrounding rooms. It was assumed that if the unit is operating (*i.e.*, blower on), the leaked refrigerant would be drawn into the ducts and blown into a downstream room (see row 3 below).
2	A leak occurring in the outside portion of the split heat pump system.	This could be due to a part failure (*e.g.*, a feed-through plug or other part).
3	A leak occurring in a heat pump system while the unit is operating (*i.e.*, blower on).	With the blower on, the refrigerant could be blown through the duct into a downstream room where an ignition source could be located.
4	A leak occurring in the air handler while the unit is idle and prior to it being turned on.	In such a case, the refrigerant could accumulate to a flammable concentration in the air handler itself. If a heating coil or some other potential ignition source (*e.g.*, an electrostatic air cleaner) becomes active before the refrigerant dissipates, the refrigerant could be ignited.
5	A leak occurring while the HVAC system is idle with the refrigerant diffusing back through the return air ductwork.	In this case, the refrigerant would leak into the room supplying the return air.
6	A leak occurring inside a wall due to rupture of refrigerant piping within the wall.	Such a leak could be due to human error (*e.g.*, home construction activity).
7	A leak occurring during HVAC system repair.	This could occur either as a result of improper recovery or recharging of refrigerant during work or due to faulty procedures used to test for a pre-existing leak (*e.g.*, a propane torch).

The residential scenarios identified by AHRTI included refrigerant leakage in residential utility closet spaces; whereas the commercial applications included leakage in a kitchen of a small restaurant, walk-in cooler, and a convenience store. These applications represent residential split, roof mounted commercial kitchen air conditioning units and walk-in and reach in type refrigeration units.

Computational fluid dynamics (CFD) modeling conducted by previous research provided refrigerant concentration results similar to those obtained from dispersion experiments. In the residential application (AHRI Project 8004), the CFD modeling predicted a potential for attaining concentrations greater than the lower flammability limit (LFL) for relatively large refrigerant leakage rates (78 g/s) with the utility closet door closed. With smaller leakage rates (1.5 g/s) and greater charge released, the refrigerant mixed quickly in the environment and did not demonstrate concentrations above the lower flammability limit (LFL).

In the commercial application (AHRI Project 8009), concentrations greater than LFL were observed in the area immediately in front of the leak.

Goetzler and Burgos[4] reported results of refrigerant concentration mapping from a slow leak with start leak rate of 4 g/s and a catastrophic leak with a start leak rate of 360 g/s for HFC-32 refrigerant in a 2.41 x 3.63 x 2.25m (7ft 11in x 11ft 11in x 7ft 4.5in) room. The results indicate that the concentration is transient and dependent upon release rate and location. In the Goetzler study, for the catastrophic leak rates, concentration was above the R-32 LFL (14.4 % by volume) at a location close to the leak source, though the gas sampling method used limited sampling from the room at discrete times.

Goetzler, et al.[5] reported a risk analysis for Class A2L refrigerants in commercial rooftop units. The investigation included a range of scenarios for which CFD simulations were developed. In these scenarios, leakage was assumed to have occurred either in the evaporator or the condenser with the blower fan off or on. The leakage entered the conditioned space horizontally (for kitchen scenario) or vertically (for office room scenario) through the supply 460 x 460mm (18 x 18 in) grill openings. The CFD simulations showed that refrigerant can accumulate in concentrations above the LFL under the scenario conditions. With the blower ON, the refrigerants dispersed quickly and resulted in refrigerant concentrations lower than the LFL for the refrigerant and air mixture.

UL staff reviewed the previous AHRI reports (AHRI 8004, AHRI 8009, and AHRI 8016 [6]) to obtain insights from the CFD analysis, and also performed additional CFD simulations for the test room configuration used in calibration and parametric tests.

[4] William Goetzler, Javier Burgos, Study of Input Parameters for Risk Assessment of 2L Flammable Refrigerants in Residential Air Conditioning and Commercial Refrigeration Applications, AHRAE Report RP-1580, (2012).

[5] Bill Goetzler, Matt Guernsey, San Faltermeier, Michael Droesch, “Risk Assessment of Class 2L Refrigerants in Commercial Rooftop Units,” AHRI Project 8016, Air-Conditioning, Heating & Refrigeration Institute, (2016).

[6] AHRI Project 8016 Final Report, “Risk Assessment of Class 2L Refrigerants in Commercial Rooftop Units”, Air Conditioning, Heating, and Refrigeration Institute, 2111 Wilson Blvd., Suite 500, Arlington, VA 22201.

2.1. AHRI Reports

The key findings from the AHRI reports, as applicable to this project, are summarized in Table 3.

Table 3 – Summary from AHRI Reports

AHRI Report	CFD Scenarios	Comments
Risk Assessment of Residential Heat Pump Systems Using A2L Flammable Refrigerants (AHRI 8004)	**Geometries:** Attic, basement, garage, and utility closet **Refrigerants:** R-32; R-1234ze(E) **Release Conditions:** 170 g/s and 78 g/s.	The concentrations in the utility closet were above Lower Flammability Limit (LFL) for approximately 70 s after release with the door closed and 20 s when the door was open. The concentrations in other geometries were generally lower than the LFL except for a small region in front of the leak jet.
Risk Assessment of Refrigeration Systems Using A2L Flammable Refrigerants (AHRI 8009)	**Geometries:** Outdoor condenser, Convenience store; Lunch counter; and Walk-in cooler/kitchen. **Refrigerants:** R-32; R-1234yf; R-1234ze(E) **Release Conditions:** Not provided in report	Concentrations greater than LFL were observed immediately in front of leak. This is likely due to relative high velocity of the leak. R-32 concentrations were generally lower than the LFL.
Risk Assessment of Class A2L Refrigerants in Commercial Rooftop Units (AHRI 8016)	**Geometries:** Kitchen and office settings with roof mounted units; considered supply, return and exhaust air. **Refrigerants:** R-32; and R-1234yf **Condenser/Evaporator Pressure and Temperature:** R-32: 473/148 psi and 125 °F R-1234yf: 197/58 psi and 125 °F Release Conditions: Natural pressure decay starting at 300 g/s (R-32) and 170 g/s (R-1234yf)	Release vents from supply duct were 18 x 18 in. The release was from a grill horizontally in kitchen scenario; and was in a vertically downward direction in office scenario.

In the AHRI 8009 and 8016 projects, the refrigerant was released from 3/8 in (9 mm) tubing. With this size orifice it is expected that the release occurs at a relatively high velocity, causing the release jet to mix with the air via turbulence. This may be one of the reasons for a relatively small volume of gas mixture in front of the release jet where the mixture concentration is higher than the LFL.

In all three AHRI projects the CFD code modeled the refrigerant release as vapor only. There are considerable difficulties in modeling a 2-phase refrigerant release.

2.2. UL CFD Analysis

This UL investigation performed CFD analysis to investigate the influence of refrigerant release rate, location, and opening size on the spatial and temporal differences in refrigerant concentrations in the test room geometry using R-32 as the refrigerant. The results were used to identify locations for placement of ignition sources due to concentration measurements where the refrigerant mixture was expected to be above the LFL.

The test room geometry was a room 2.4 x 3.6 x 2.4 m (W x L x H) used in Task 1. The test room contained a single obstruction 3.0 x 6.0 x 3.0 ft (0.91 x 1.83 x 0.91 m) placed on the floor in the center of the room with the long side facing the discharge location. CFD simulations were performed using the Fire Dynamics Simulator[7] (FDS) software, version 6.4.0 with a release from 50x50 mm (2.0x2.0 in) and 300x300mm (12x12 in) square openings for flows representing high and low velocity release into the test room respectively. While these opening sizes are not those selected for testing, they provide a understanding of the influence of release velocity on refrigerant mixing with ambient air and enable comparison of resulting refrigerant concentrations with refrigerant flammability limits. The release orifices were square because FDS utilizes a rectilinear computational mesh within its computational domain. The grid size for the simulations was 50 x 50 x 50 mm. It was recognized that the grid was coarse, but resulted in faster simulations and enabled insights into refrigerant concentrations in the test room geometry of interest. The simulations did not include ignition. The following assumptions were used in the simulations:

- The temperature of the refrigerant at the release was 8 °C (46 °F);
- The refrigerant will behave like an ideal gas at the release opening.

[7] National Institute of Standards and Technology, Fire Dynamics Simulator (FDS) and Smokeview (SMV), https://pages.nist.gov/fds-smv/

A matrix of the simulations performed is provided in Table 4. The total mass release was equivalent to the amount of refrigerant necessary to reach 50% of the LFL of R-32 based upon the total room volume when evenly distributed throughout the room.

Table 4 – Matrix of CFD Simulations

Refrigerant	Simulation	Release rate (g/s)	Total Release (kg)	Release Opening Size (mm)	Average Release Velocity (m/s)	Release Location above Floor (m)
R-32	1	100	3.24	50	21.7	2.2 (top)
	2	13.5	3.24	50	2.9	2.2 (top)
	3	100	3.24	300	0.6	2.2 (top)
	4	13.5	3.24	300	0.1	2.2 (top)
	5	100	3.24	50	21.7	0.2 (bottom)
	6	13.5	3.24	50	2.9	0.2 (bottom)
	7	100	3.24	300	0.6	0.2 (bottom)
	8	13.5	3.24	300	0.1	0.2 (bottom)

Still images from the simulations at different times were captured for discussion. The color code scale in the scenes represents refrigerant concentration with blue equivalent to zero concentration of R-32 and red as 35% volume fraction (Note: the UFL is 0.293 mole fraction and appears in the red area). A black band is shown in the scenes and represents an area where the concentration is at the lower flammability limit (LFL = 0.144 mole fraction). Thus, color codes on the scale above the black band represent concentrations higher than the LFL. The still images that follow show a vertical slice down the centerline long axis of the test room.

2.2.1. Release from 2.2 m height

Simulation 1(Figure 2) shows that a high velocity (e.g., 100 g/s and 50 mm release opening) release results in a jet in the test room that causes turbulent mixing with the ambient air and yields relatively low concentrations of the refrigerants in the test room. The region of gas above LFL is confined to a small volume in front of the release location.

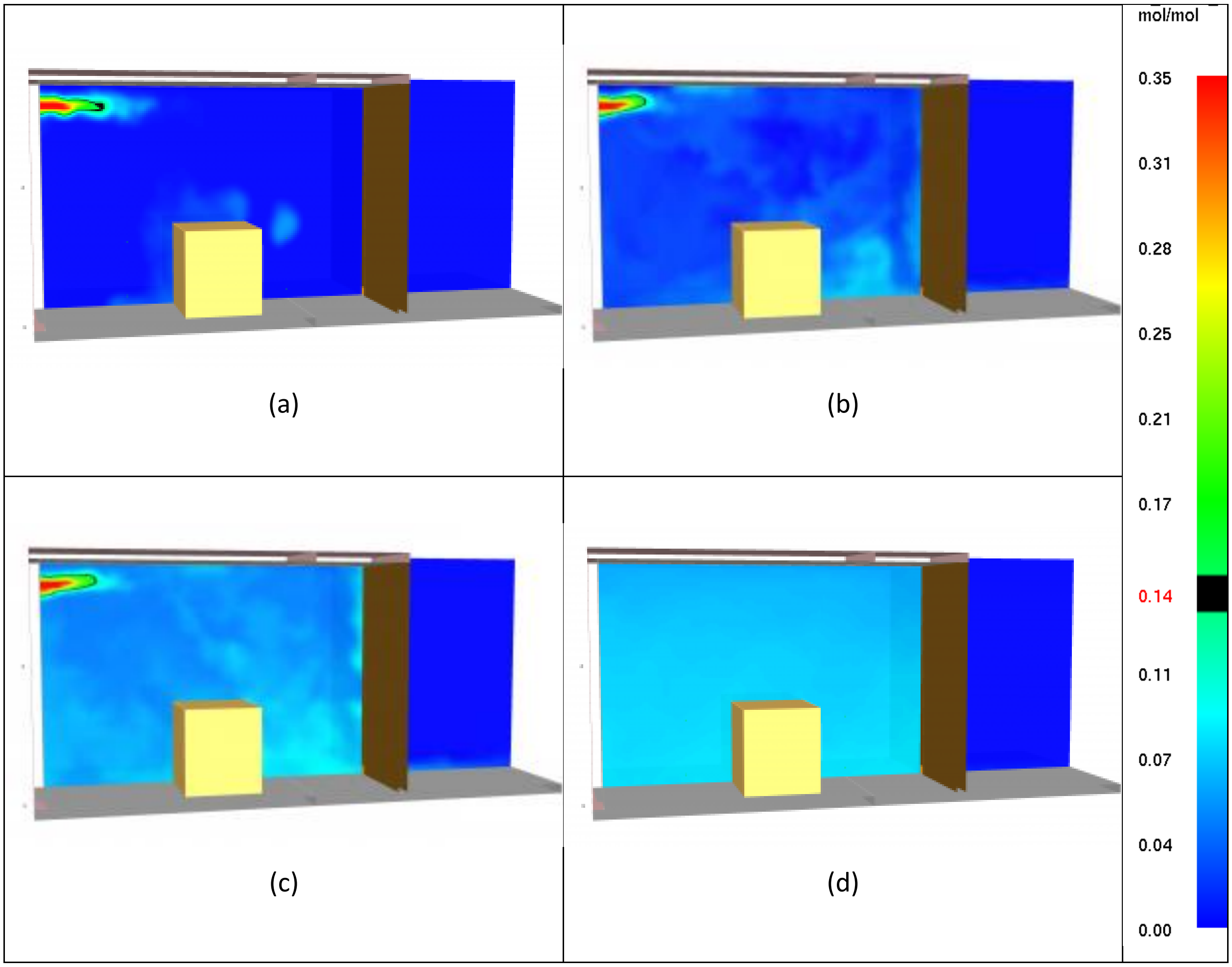


Figure 2 – Still images from FDS simulation 1 at times: (a) 5 s (b) 15 s (c) 30 s (d) 90 s

Increasing the release opening to 300 mm (Simulation 3, Figure 3) reduces the release velocity and results in pooling of the refrigerant at the floor level with relatively rich refrigerant-air mixtures at the floor level over time. Refrigerant released from the orifice immediately falls to the floor level. At the completion of the discharge the volume near the floor shows concentrations between the LFL and UFL.

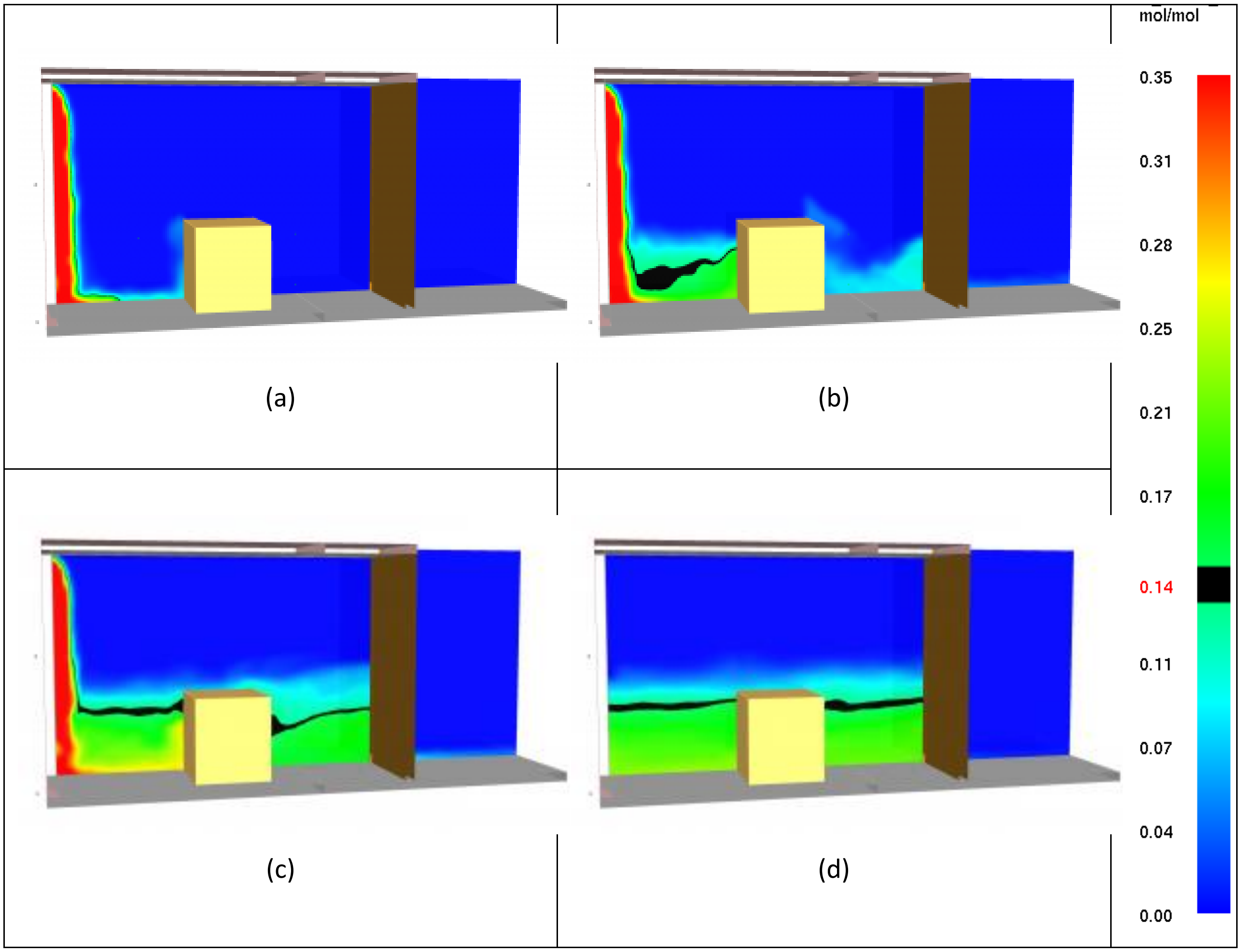


Figure 3 – Still images from FDS simulation 3 at times: (a) 5 s (b) 15 s (c) 30 s (d) 90 s

In simulation 2, the release rate is 13.5 g/s with a 50 mm release size, at a release height of 2.2 m (Simulation 2, Figure 4) resulting in the refrigerant entering with less turbulence. Mixing is driven primarily by buoyancy and less by velocity. A small volume of flammable mixture is shown below the release orifice.

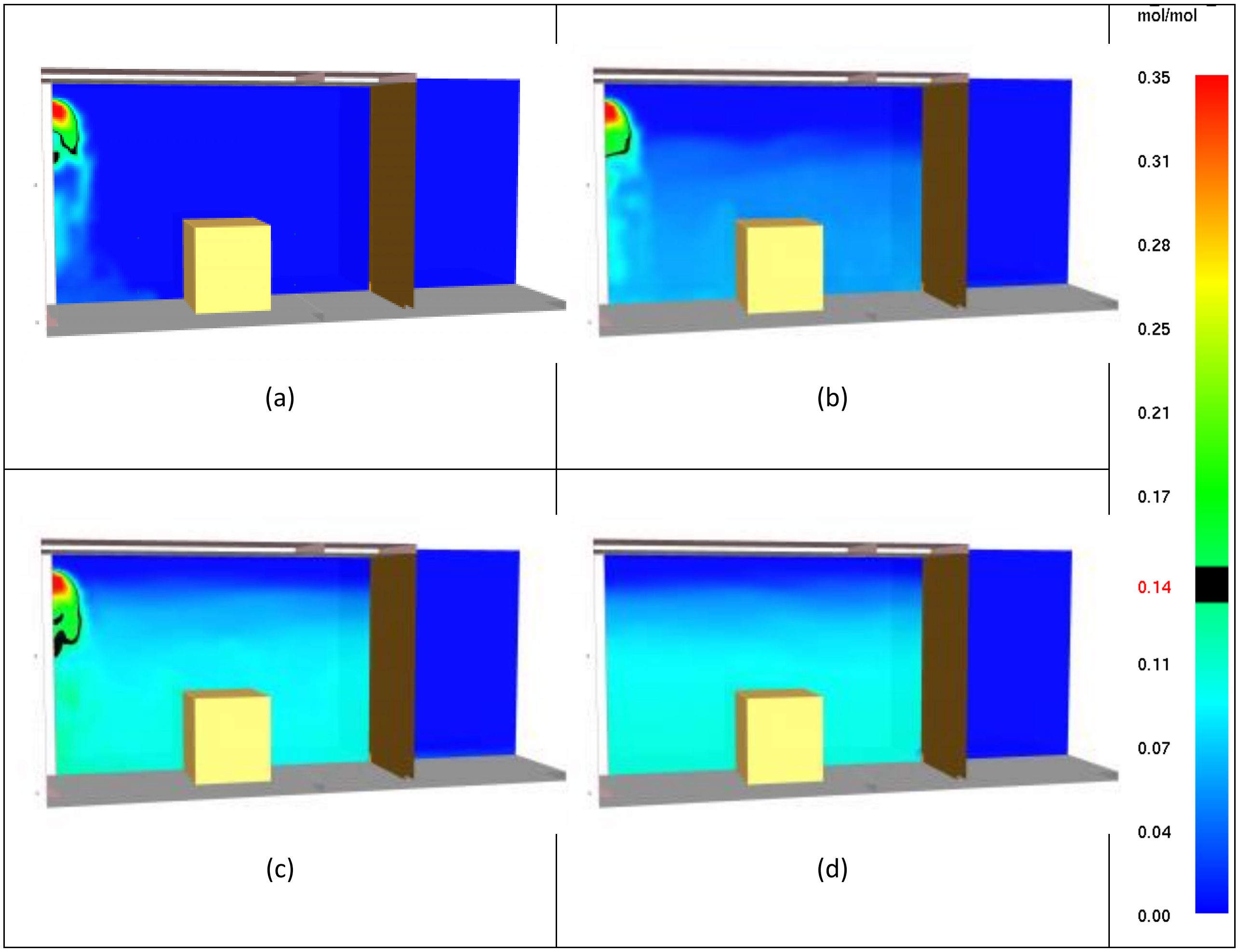


Figure 4 – Still images from FDS simulation 2 at times: (a) 5 s (b) 120 s (c) 240 s (d) 300 s

A combination of lower release rate and larger release opening (Simulation 4) facilitates more refrigerant pooling. A large volume of refrigerant/air at or above the lower flammability limit is shown in Figure 5. The volume of refrigerant between lower and upper flammability limits is approximately 1 ft. deep. This region provides a potential for ignition.

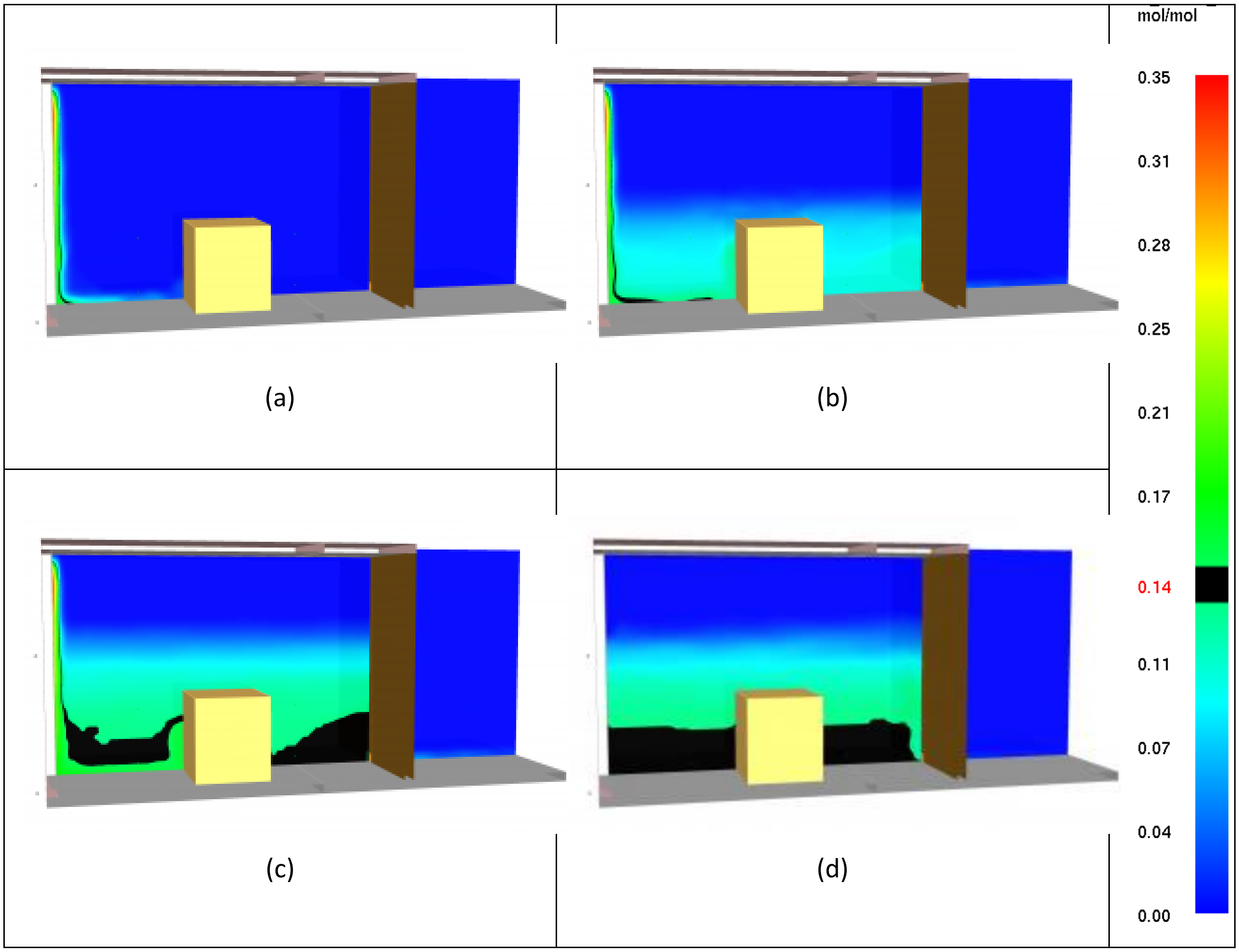


Figure 5 – Still images from FDS simulation 4 at times: (a) 5 s (b) 120 s (c) 240 s (d) 300 s

2.2.2. Release from 0.2 m height

For a release rate of 100 g/s from the 50 mm release opening at 0.2 m height (Simulation 5), mixing is facilitated by the presence of the obstruction (e.g., furniture) and creates approximately 1 ft. deep mixture of refrigerant and air at the floor level that is above the LFL, as shown in Figure 6.

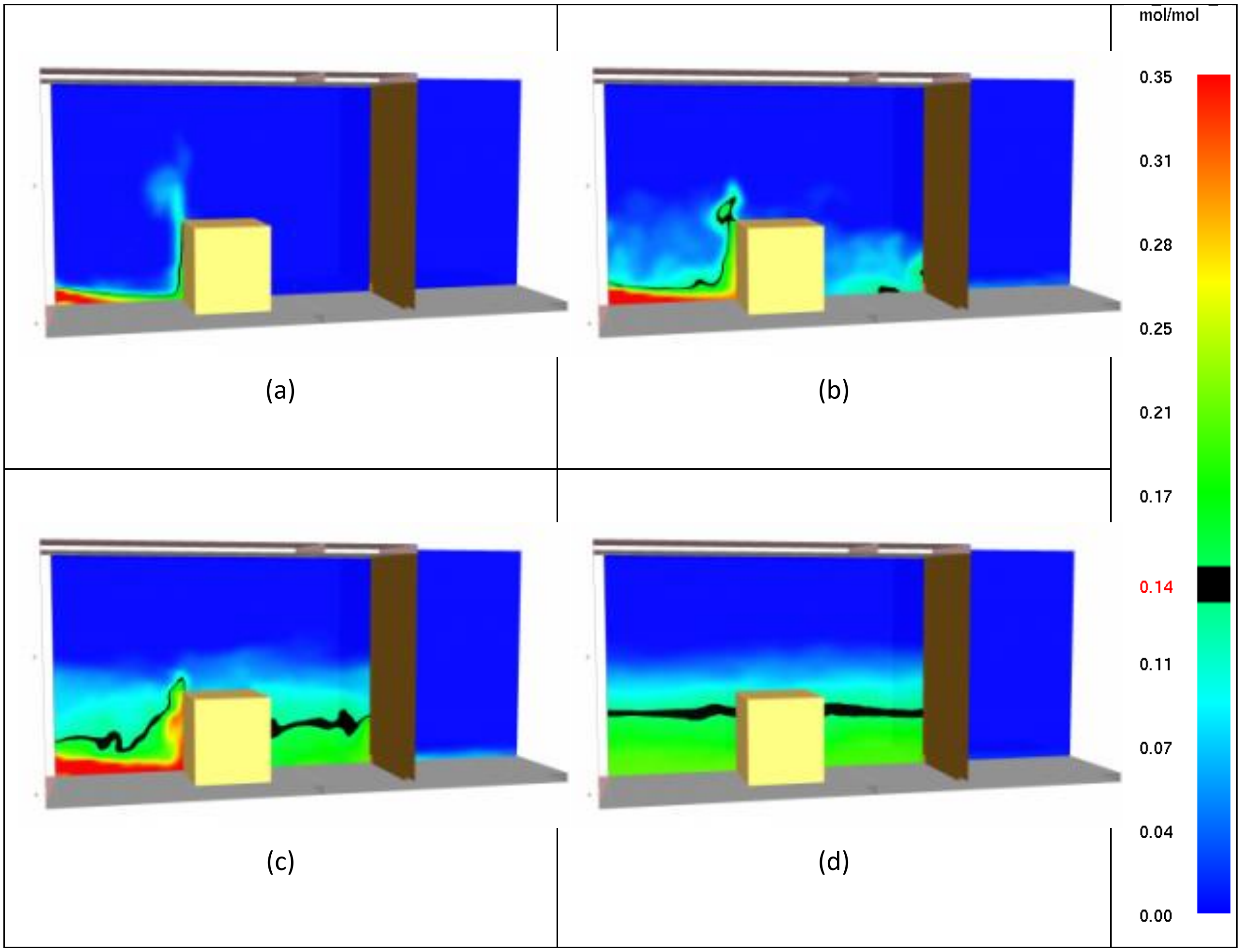


Figure 6 – Still images from FDS simulation 5 at times: (a) 5 s (b) 15 s (c) 30 s (d) 90 s

Increasing the opening size but with the same release rate (Simulation 7), results in refrigerant mixture at the floor level that is above the upper flammability limit as shown in Figure 7. This is expected to dissipate through diffusion over time to develop mixture in the flammability zone.

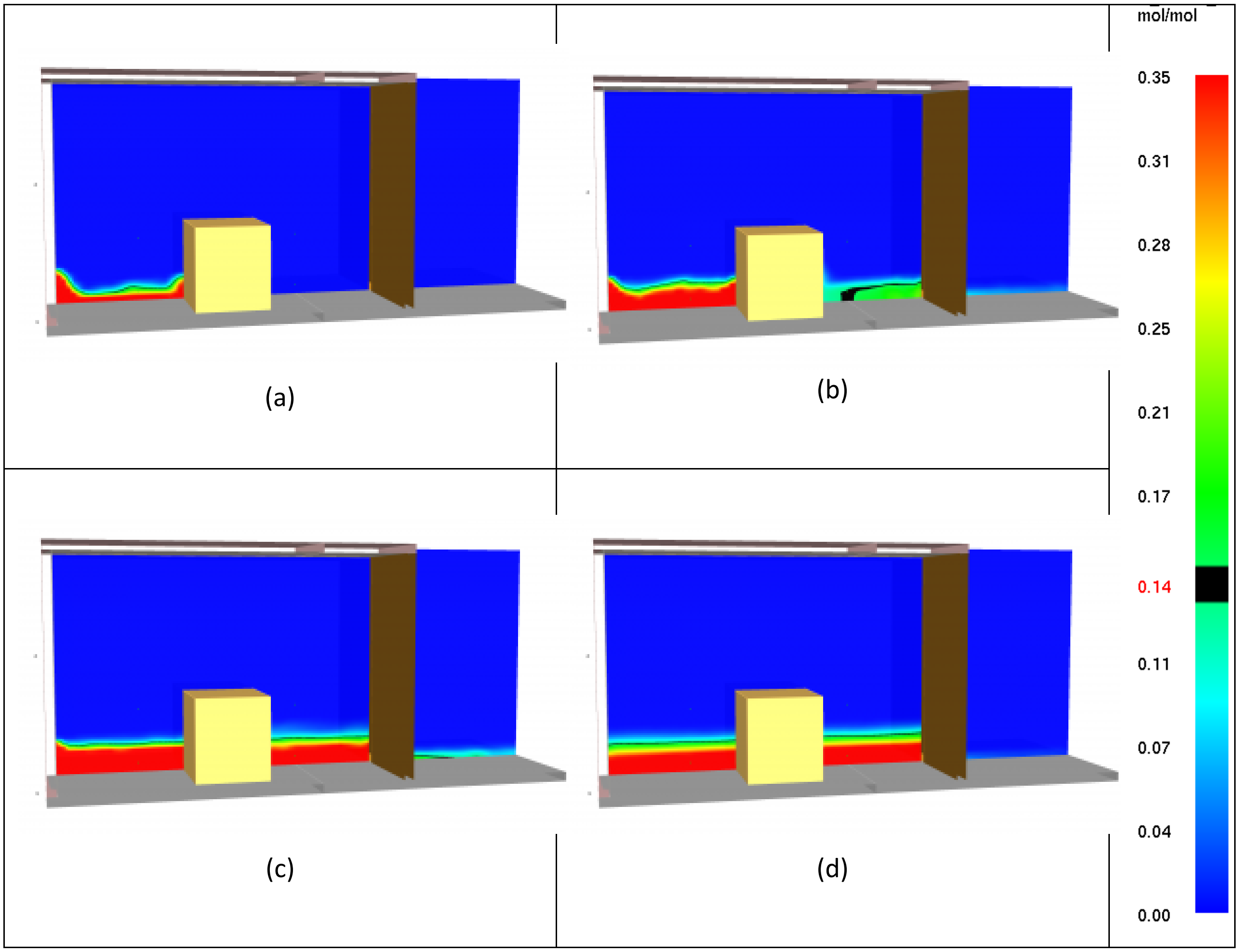


Figure 7 – Still images from FDS simulation 7 at times: (a) 5 s (b) 15 s (c) 30 s (d) 90 s

Reducing the flow rate with 50 mm opening (Simulation 6) also results in a refrigerant rich mixture at the floor with a potential for ignition. The scenes for this simulation are presented in Figure 8.

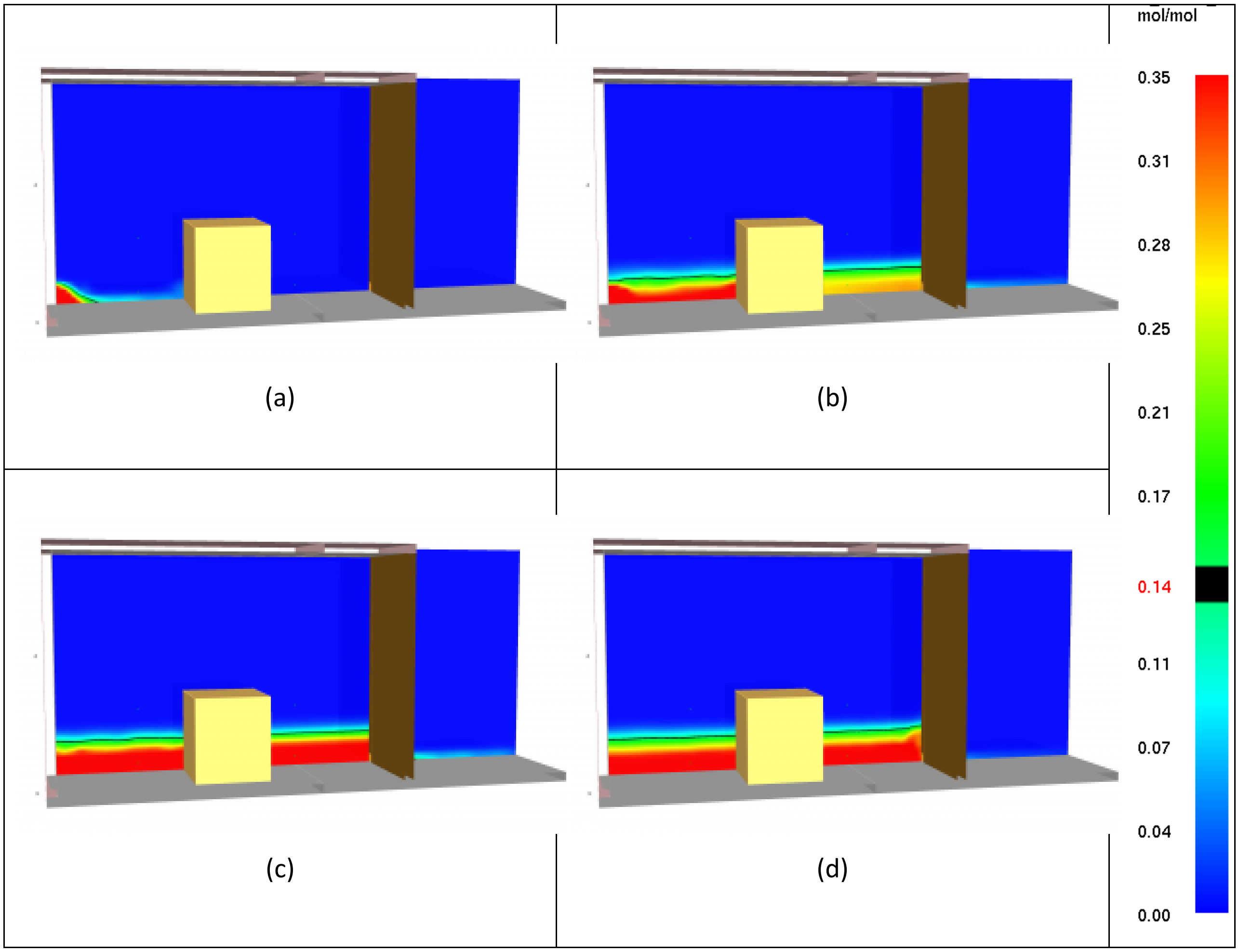


Figure 8 – Still images from FDS simulation 6 at times: (a) 5 s (b) 120 s (c) 240 s (d) 300 s

A similar result was obtained with combination of low release rate and larger release opening (Simulation 8) as depicted in Figure 9.

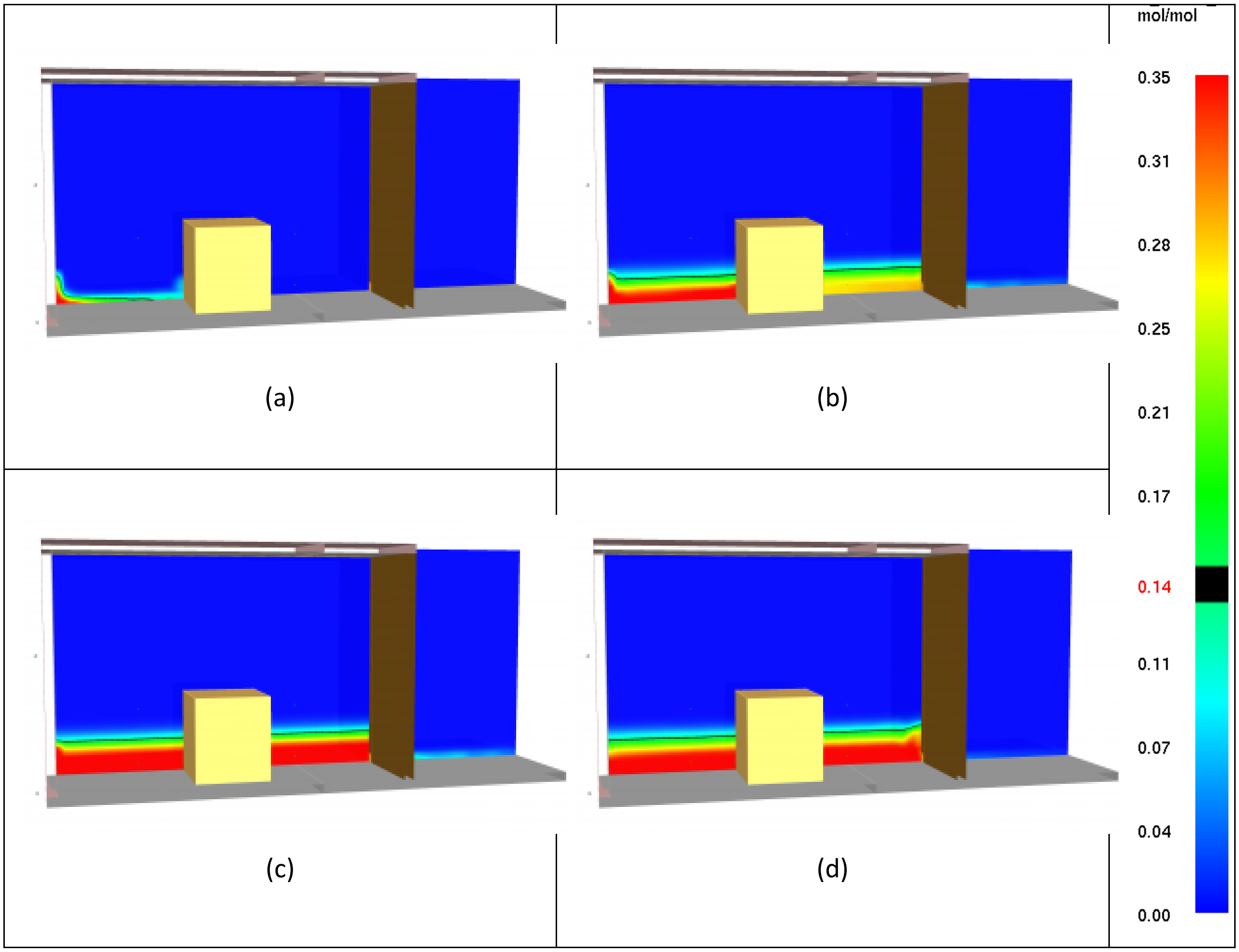


Figure 9 – Still images from FDS simulation 8 at times: (a) 5 s (b) 120 s (c) 240 s (d) 300 s

The CFD analysis provided useful insights into the effect of release opening size, location and rates on the refrigerant mixtures in the test room of geometry used in the calibration tests. The results facilitated in identifying locations of refrigerant concentration measurements and ignition sources. Since the test conditions used in the calibration tests differed from the inputs used in the CFD simulations, a qualitative comparison and discussion of the CFD results with calibration tests is presented in Appendix A Comparison of CFD Simulations with Calibration Test Experiments.

2.3. Summary of Findings from CFD Analysis

1. The simulations assisted in better understanding the potential increase in refrigerant concentration under different leak conditions.
    a. Release at a high velocity from 2.2m height will result in a jet that mixes with the ambient air resulting in concentrations in the test room below the lower flammability limit. However, if released from a lower level, obstructions will break up the jet and develop regions with concentrations above the LFL at the floor level.
    b. Release at low velocity allows the refrigerant at 2.2 m height to fall more gently in the room but mixes with the air to develop relatively small volume of flammable mixture. However, if released from lower level, it generally results in pooling of flammable refrigerant-air mixtures.
2. The refrigerant concentrations results from the simulations show that the area in between the obstruction and release opening would provide the most likely location for potential ignition of refrigerant-air mixtures.

3. The simulations were in qualitative agreement with findings from previous AHRI investigations (AHRI 8004, 8009, and 8016).

3. Task 1 – Refrigerant Leak and Ignition Testing Under a Controlled Environment

Based upon input from the AHRTI PMS, the refrigerant release scenario in Task 1 simulates a break in the condenser line before the expansion valve as shown in Figure 10.

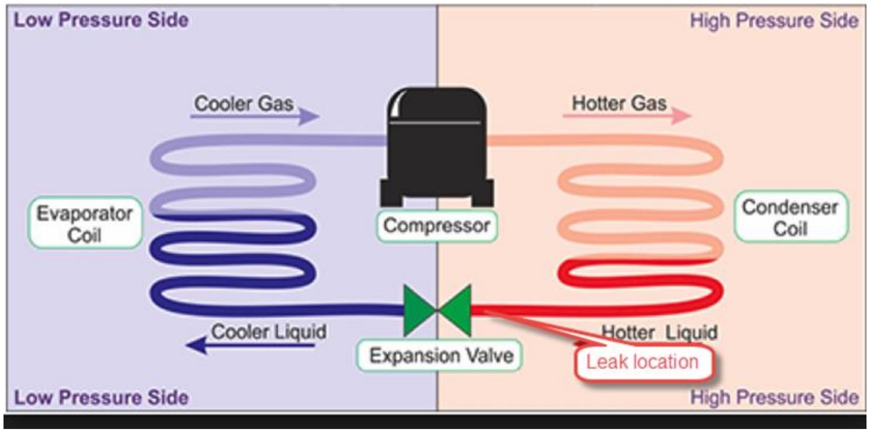


Figure 10 – Refrigeration Leak Scenario

The refrigerant leak quantity (i.e., mass) for each refrigerant was equivalent to the amount of refrigerant necessary to yield an average room concentration equivalent to 50% of a given refrigerant's lower flammability limit (LFL) based on the total room volume. The release quantities at a reference temperature of 23 °C and a room volume of 768 ft^3 (21.75 m^3) are shown in Table 5 using the refrigerant properties in Table 1. With the added obstruction of a rectangular box to simulate furniture, the room volume was reduced to 714 ft^3 (20.22 m^3). Discharge quantities for the nonflammable refrigerants were based on achievement of 5% concentration by volume.

Table 5 – Refrigerant Release Properties and Quantities (Task 1)

Parameter	R-22	R-32	R-410A	R-452B
Target for Discharge	5% v/v in room volume	50% LFL	5% v/v in room volume	50% LFL
Discharge Quantity (kg)	3.75	3.25	3.15	3.36

3.1. 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, acid gases (particularly hydrogen fluoride gas and hydrogen fluoride acid), electric shock, frostbite, and mechanical hazards. Potential hazards to the environment included releases of refrigerant gases and combustion products. Hazards were addressed by:

- Elimination.
- Engineering controls.

- Administrative controls.
- Personal protective equipment.

3.1.1. 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 laboratory and stored in a nearby warehouse. 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.

3.1.2. Engineering Controls

The UL Large Fire Laboratory is equipped with a regenerative thermal oxidizer (RTO) exhaust system which processes all exhaust gases from the lab through a high temperature ceramic bed to insure their complete oxidation. When the RTO system is operating, the fire lab is kept at a negative pressure to direct all exhaust from the fire lab into the RTO intake duct.

To optimally isolate gaseous hazards within the fire lab resulting from the refrigerant experiments, a 30 ft. x 30 ft. x 8 ft. high test facility was constructed within the fire lab. The tests were conducted within temporary mock-up rooms built within this test facility. The test facility included exhaust duct work directly connected to the RTO intake ductwork to exhaust post-experiment gases directly to the RTO. This limited the amount of gases released into the laboratory, and maximized the air exchange rate within the test facility. However, the test room itself could not be made leak tight due to the possibility of room overpressure during a deflagration involving test gases. To prevent over-pressurization, the test facility and test rooms included deflagration vents, sized by calculations from NFPA 68: Standard on Explosion Protection by Deflagration Venting.

Some tests included simulating refrigerant leakage from equipment that included combustible materials. A sidewall sprinkler was installed into the test room that enabled remote extinguishment of aforementioned equipment to prepare against a scenario where it ignited as a result of thermal exposure.

Mechanical hazards were addressed by providing machine guarding for any exposed and moving parts associated with test equipment.

All necessary actions required to initiate and provide input to tests were designed such that each action could be conducted from outside the laboratory. In this way, test personnel were not required to be in the test room, test facility or laboratory, providing several degrees of separation between project staff and any potential hazard generated during testing.

3.1.3. Administrative Controls

Standard operating procedures (SOPs) were developed in order to provide laboratory staff with guidance for safe experiment 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 an experiment, all staff evacuated the laboratory. Actions needed to initiate and administer a test were conducted remotely from a separate data room.

During and after an experiment, the atmosphere inside the test facility was monitored for respiratory hazards. Before any staff was permitted entry into the laboratory, the test facility was ventilated with the RTO for a length of time corresponding to at least 15 complete air changes through the test facility or until an infrared based refrigerant leak detector indicated that unburned refrigerants were completely exhausted. In addition, an open-path Fourier Transform Infrared Spectrometer (FTIR) was used to measure the atmosphere inside the laboratory. The IR absorption spectra of expected toxic gas hazards were monitored prior to determine whether or not a gaseous hazard existed. Unexpected IR spectra were analyzed, and if not presenting a known hazard, the determination was made that the laboratory was safe to enter with a full-face respirator and cartridge for protection against organic vapors and particulates. A separate gas detector for hydrogen fluoride gas (the chief gas of concern) was kept on standby in the event that the FTIR malfunctioned.

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.

3.1.4. Personal Protective Equipment

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

Additional protective equipment included:

- Long sleeve shirts and long pants.
- Full face masks provided with P100/organic vapor cartridges (3M part 4JG16).
- 9-mil neoprene gloves.
- Refrigerant operations were conducted by personnel trained and authorized to do so.

3.1.5. Equipment Considerations

Aside from the damaging effects of fire, the production of hydrogen fluoride (HF) and other corrosive compounds tends to damage equipment and cables that are not directly exposed to fire. In this project, video cameras needed frequent replacement due to etching of lenses or corrosion of power and video cable connectors. Additionally, installed humidity probes failed after the first exposure to HF. Hand-held humidity probes were used to monitor initial humidity conditions prior to each test.

The calibration and parametric series of tests showed that the use of aluminum tape should be reduced to a bare minimum because it tends to react with the refrigerant combustion products. In later testing, drywall compound was used to seal the test room rather than aluminum tape.

3.2. Test Facility, Instrumentation and Equipment

3.2.1. Test Facility and Test Structure

3.2.1.1. Conditioned Test Facility

All experiments for Task 1 were performed in a 30 ft. by 30 ft. by 8 ft. (9.14 x 9.14 x 2.44 m) test facility, climate controlled to provide the temperature and humidity conditions required by the experiments, as shown in Figure **11**. The ceiling was constructed using two layers of 3-in. rigid insulation between layers of ½ in. drywall attached to the moveable ceiling of the lab. The ceiling was lowered past the top plate of the room walls to fit into the room and the perimeter was sealed with high expansion fire retardant foam and aluminum tape. The walls were 2 in. by 4 in. wood stud, 16 in. on center construction with R-15 insulation in the stud bays. The walls were sheathed with lightweight ½ in. drywall. To control gas permeability (as a measure of laboratory safety), the drywall was coated with one layer of Promar 200 primer [8] and two coats of Sherwin Williams pre-catalyzed water-based epoxy, K45-150 series. The walls were assembled over two layers of foam sill sealer [9]. The room featured a backdraft damper to provide make-up air during room exhausting and a deflagration vent in case of rapid pressure increase due to refrigerant ignition. Two 36 in. by 80 in. wood framed solid-core doors were included to allow access to the room. These doors were sealed with foam rubber gaskets during testing. Additionally, one wall of the room included two ports to exhaust the room; one 8 in. diameter duct operated with a very low draw rate and was connected to a refrigerant capture box. One 16 in. duct exhausted the room into the regenerative thermal oxidizer (RTO) after each test. The 16 in. diameter duct was controlled by a damper to exhaust the room only after a test is completed.

[8] Promar is a trade name of Sherwin Williams.

[9] Owens Corning Foam SealR.

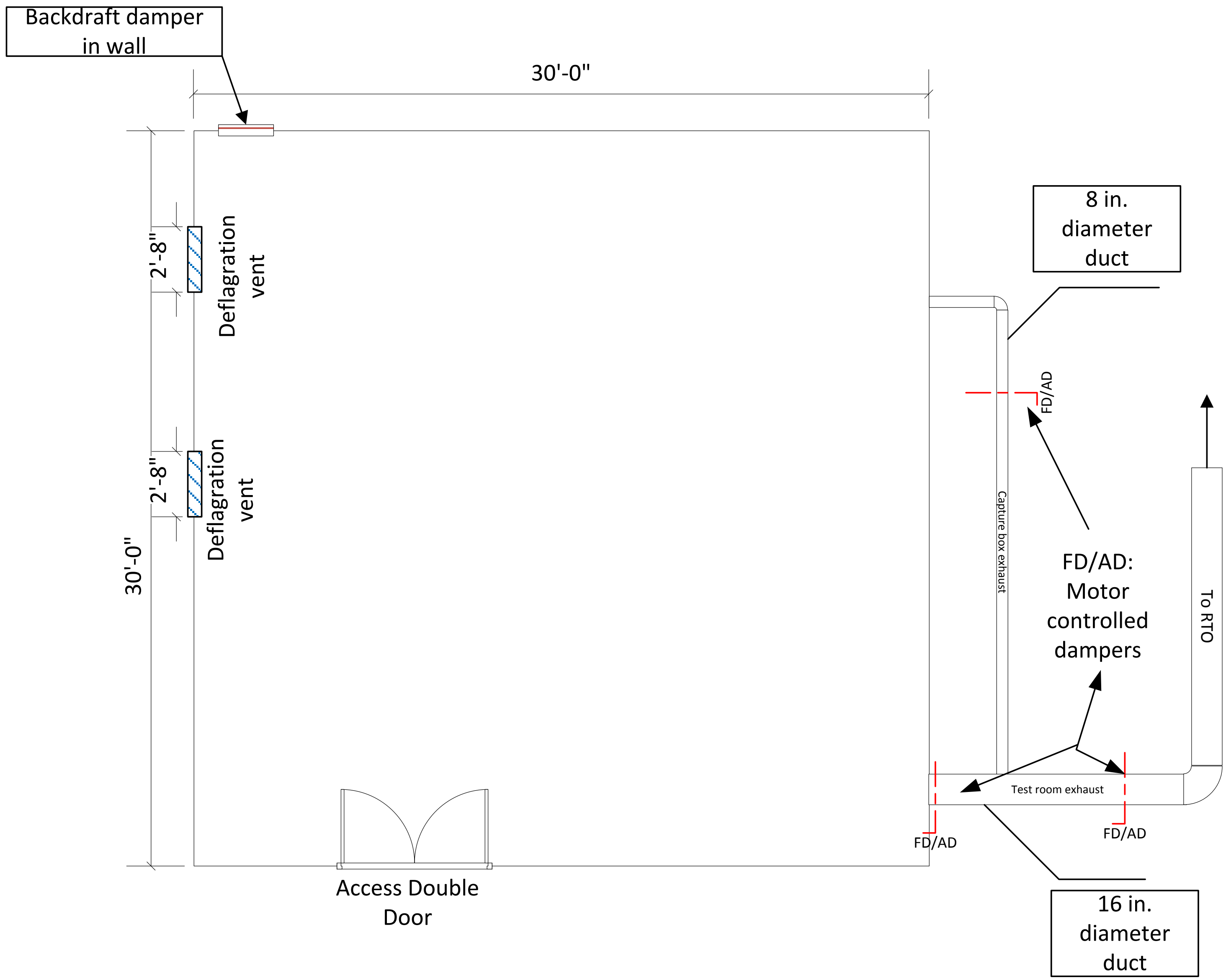


Figure 11 Conditioned Test facility

3.2.1.2. Task 1 Test Room

A 12 ft. by 8 ft. by 8 ft. (3.7 x 2.4 x 2.4m) room was constructed within the test facility to conduct tests for Task 1. Figure 12 is a drawing of the room and its features. The room was modeled after the ISO 9705 test room[10]. The test room shared a corner with the test facility such that the exhaust ports of the larger room could be utilized to exhaust the refrigerant and its combustion byproducts after each test. The walls were built with 2 in. x 4 in. wood studs located 16 in. on center. The walls were covered with lightweight ½ in. drywall; the inside face of the drywall was coated with one layer of Promar 200 primer and two coats of Sherwin Williams pre-catalyzed water-based epoxy, K45-150 series. The walls were assembled on two layers of sill sealer[11]. The test room also shared a ceiling with the test facility and the top seams of the walls were sealed with high expansion fire retardant foam and aluminum tape to prevent leakage.

The test room featured a backdraft damper and deflagration vent, in addition to the ones from the test facility. For the first 9 calibration tests (Cal01 through Cal09), the deflagration vent opening was 2 ft. – 8 in. by 2 ft tall (0.8 m x 0.6 m) and closed with a thin plastic sheet. This design allowed too much pressure to build with in the room. In one test (Cal09), the pressure was high enough to deform the walls of the test room and test facility. It was determined that the thin plastic sheet did not open soon enough to prevent the overpressure.

The deflagration vent was resized for all later tests (Cal10 and beyond) as 2 ft-8 inches wide and 3 ft. tall (0.8 m x 0.9 m), set 5 ft. (1.5 m) above the floor. Instead of a thin plastic sheet, a sliding window was installed that was manually opened after completion of the refrigerant discharge. The pressure rise data from tests Cal05 through Cal09 cannot be compared to the pressure rise data in tests beginning with Cal10 because of this change to the deflagration vent.   A 3 ft. wide by 1/8 in. (0.9 m x 0.003 m) high vertical gap was included at the bottom of the wall across from the refrigerant release equipment to simulate door gap during the experiment. A refrigerant capture box was located on the other side of the gap to capture refrigerant leakage and was exhausted into the RTO. A functioning, hollow-core door was included in the test room for access and set up, but was fully sealed during the experiments. The test room door was painted in the same manner as the inside face of the drywall. An obstruction (e.g., furniture) was simulated with a 6 ft. by 3 ft. by 3 ft. high (1.83 m by 0.91 m by 0.91 m) box in the middle of the room.

10 ISO 9705-1: Reaction to fire tests - Room corner test for wall and ceiling lining products - Part 1: Test method for a small room configuration - First Edition

11 Owens Corning Foam SealR.

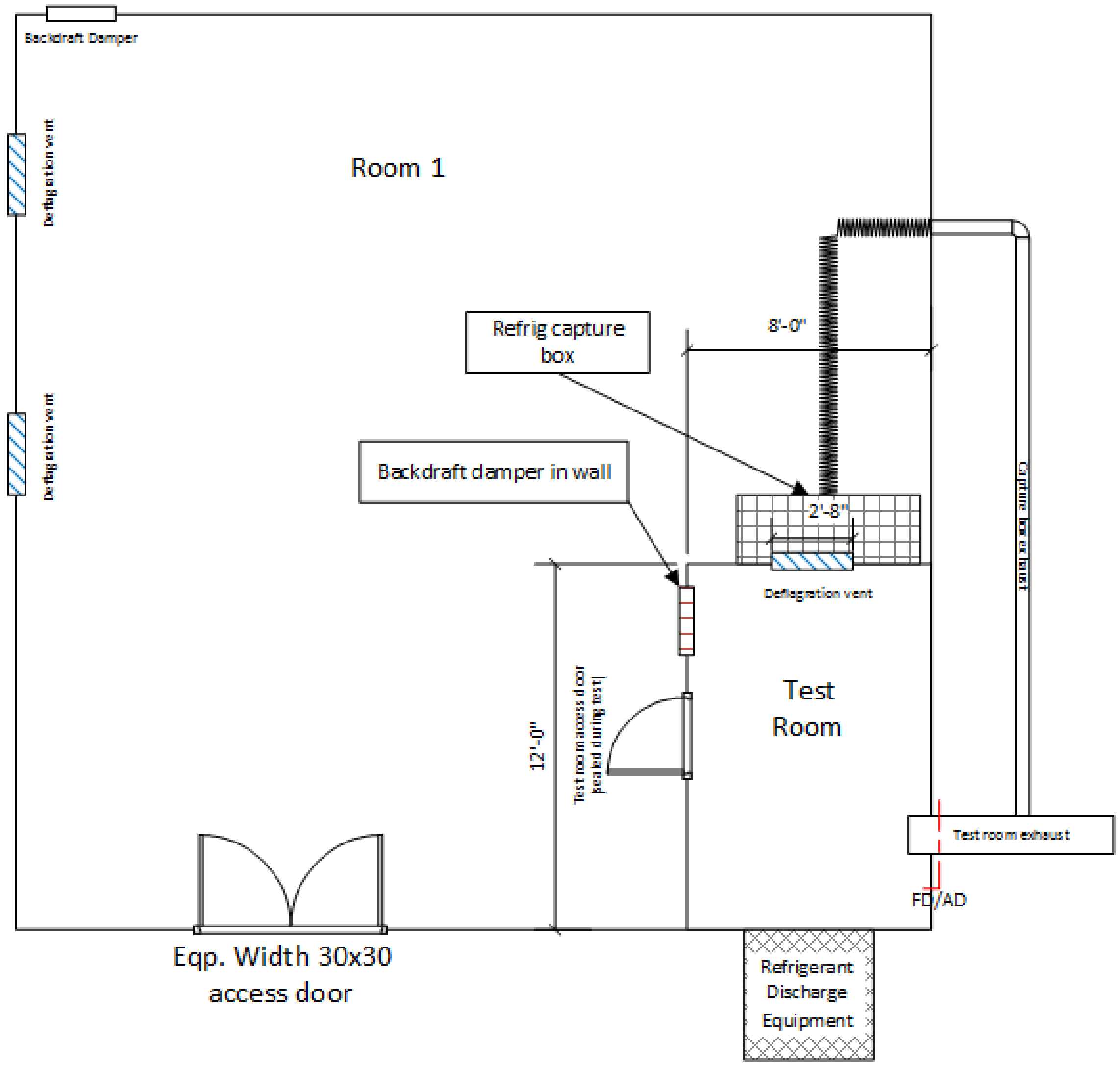


Figure 12 – Task 1 room design

3.2.2. Instrumentation

Specifications of instrumentation and equipment used throughout this project are included in Appendix D Test Instrumentation and Equipment. The data acquisition system collected all signals at the rate of 10 samples per second for all tests with the exception of the long-duration room leakage tests (Cal14 and Cal15) which were sampled at the rate of 1 sample per second. A brief summary of instrument types and locations is given below:

Temperature – The test room temperature was monitored using 0.035 in. (0.89 mm) open bead Type K thermocouples. The thermocouple response time was approximately 3.0 seconds. 47 thermocouples were located throughout the test room as shown in Figure 13. Six thermocouple arrays were placed with thermocouples at 4 in., 8 in., 12 in., and 18 in. (0.1, 0.2, 0.3, 0.46 m), above the floor and 4 in., 8 in., and 12 in. (0.1, 0.2, 0.3 m) below the ceiling. One thermocouple was placed at each of the release locations. Two thermocouples were placed near the floor at the simulated door opening.

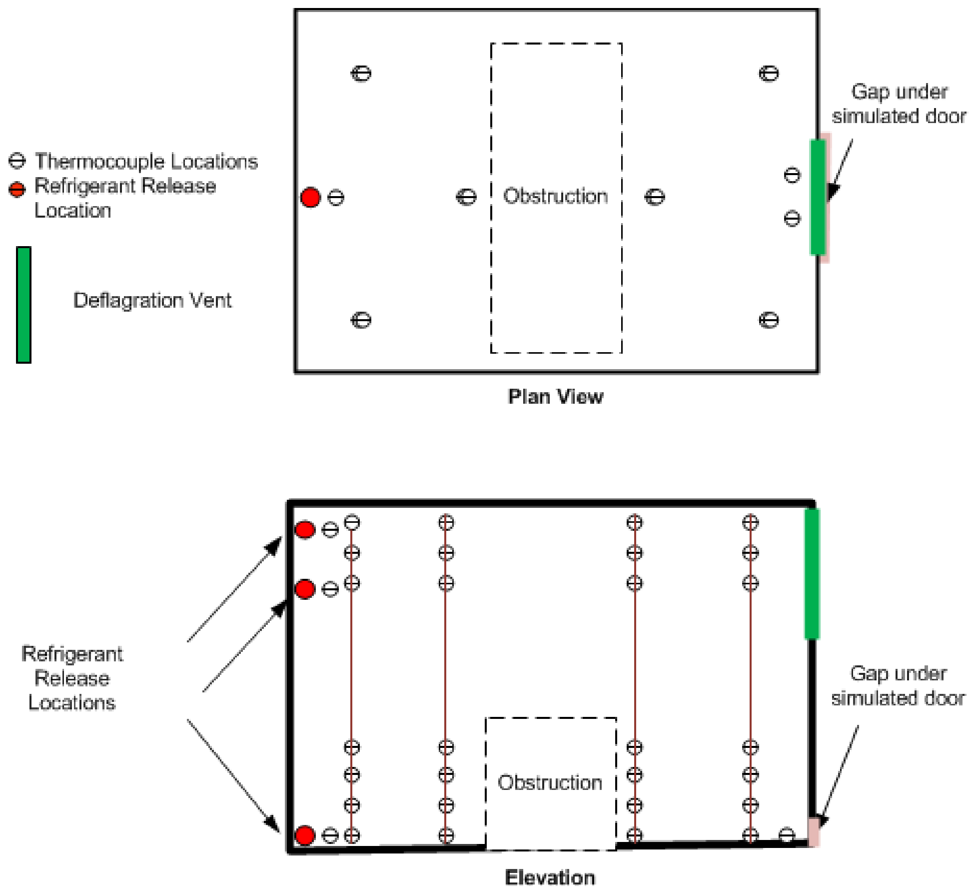


Figure 13 – Thermocouple Locations Relative to Refrigerant Release

Humidity – The test room humidity was measured with a handheld temperature and humidity combination unit. Temperature and humidity were monitored until the room conditions met the criteria to conduct a test.

Pressure – The pressure in the test room was monitored using an electronic differential pressure transducer with the range of 0 – 10 mm Hg. The pressure sensing port was located in the center of the room near the doorway.

Refrigerant Gas Concentration – The leaked refrigerant gas concentration in the test room was measured by total hydrocarbon analyzers calibrated for the specific refrigerant of interest. The sampling ports were located 1, 12, 24 and 36 in. (0.25, 0.3, 0.6, 0.9 m) above the floor.

Video – Eight high definition video cameras were used to document the test events.

Digital photography – Digital (still) cameras were used to supplement visual observation.

3.2.3. Electric arc Ignition Source

A step-up gas tube transformer was used to create an electric arc as an ignition source. The leads of the transformer were connected to a pair of tungsten rods mounted such as to leave a ¼ inch air gap. Photographs of this equipment are included in Figure 14. Note that the transformer secondary ratings are based on open-circuit voltage and short-circuit amperage.

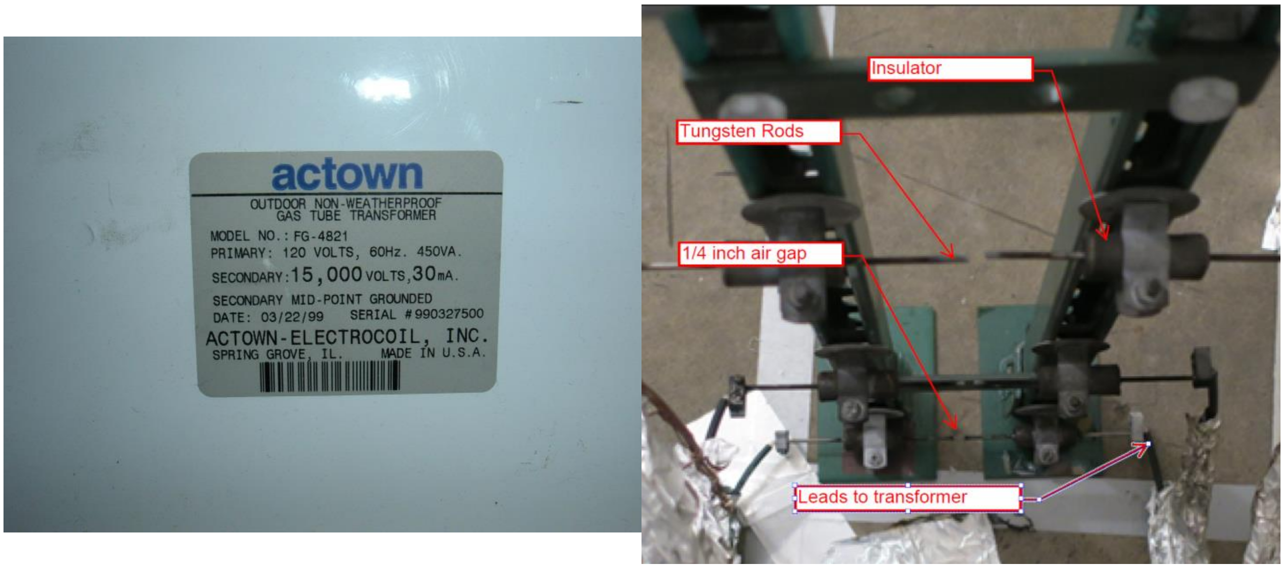


Figure 14 – Gas tube transformer and arc gap

Table 6 shows the measured rms voltage and amperage developed by each electric arc/transformer pair. The rms power of the electric arc was 17.6 watts (joules/sec). The energy of the electric arc in one-half 60 Hz cycle (8,333 µs) was 0.147 joules (147 mJ). This energy per half cycle cannot be directly compared to Minimum Ignition Energy (MIE) tests which use a single capacitive discharge with a much shorter duration (0.01 to 0.1 µs).

Table 6 – Electric arc Input Power and resulting output

Input P_{RMS}	Output per Electrode		
	V_{RMS}	I_{RMS}	P_{RMS}
watt	Volts	milliAmpere (mA)	watt
75.0	1590	11.06	17.6

Figure 15 shows a typical voltage and current trace of two 60 Hz cycles of an electric arc such as used in these experiments.

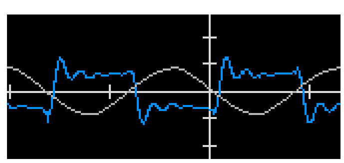


Figure 15 – Trace of current (smooth sine wave) and voltage in an electric arc

When used in testing, the electric arc transformer was continuously energized for several minutes.

3.2.4. Methodology for Refrigerant Release in Test Room

Figure 16 illustrates the refrigerant release system used in the Task 1 experiments (lubricating oil not included). The system consisted of a pressurizer tank and a release tank. The pressurizer tank assisted with maintaining the pressure in the release tank to enable liquid release to the test room at a constant rate. Prior to release, the line between the pressurizer and release tank, and release tank and mass flow meter were evacuated to a vacuum of less than 1 mmHg from service ports SV1, and SV2. To initiate the release, manual valve V1 and V2 are first opened to allow fluid communication between pressurizer and release tanks. Manual valve V3 is then opened to fill the line between the release tank and mass flow meter with liquid refrigerant. The control valve was pre-programmed to open to the position corresponding to the specified release rate to enable release into the room. The mass flow meter provides real-time feedback to the control valve to provide continuous control throughout the duration of the refrigerant release.

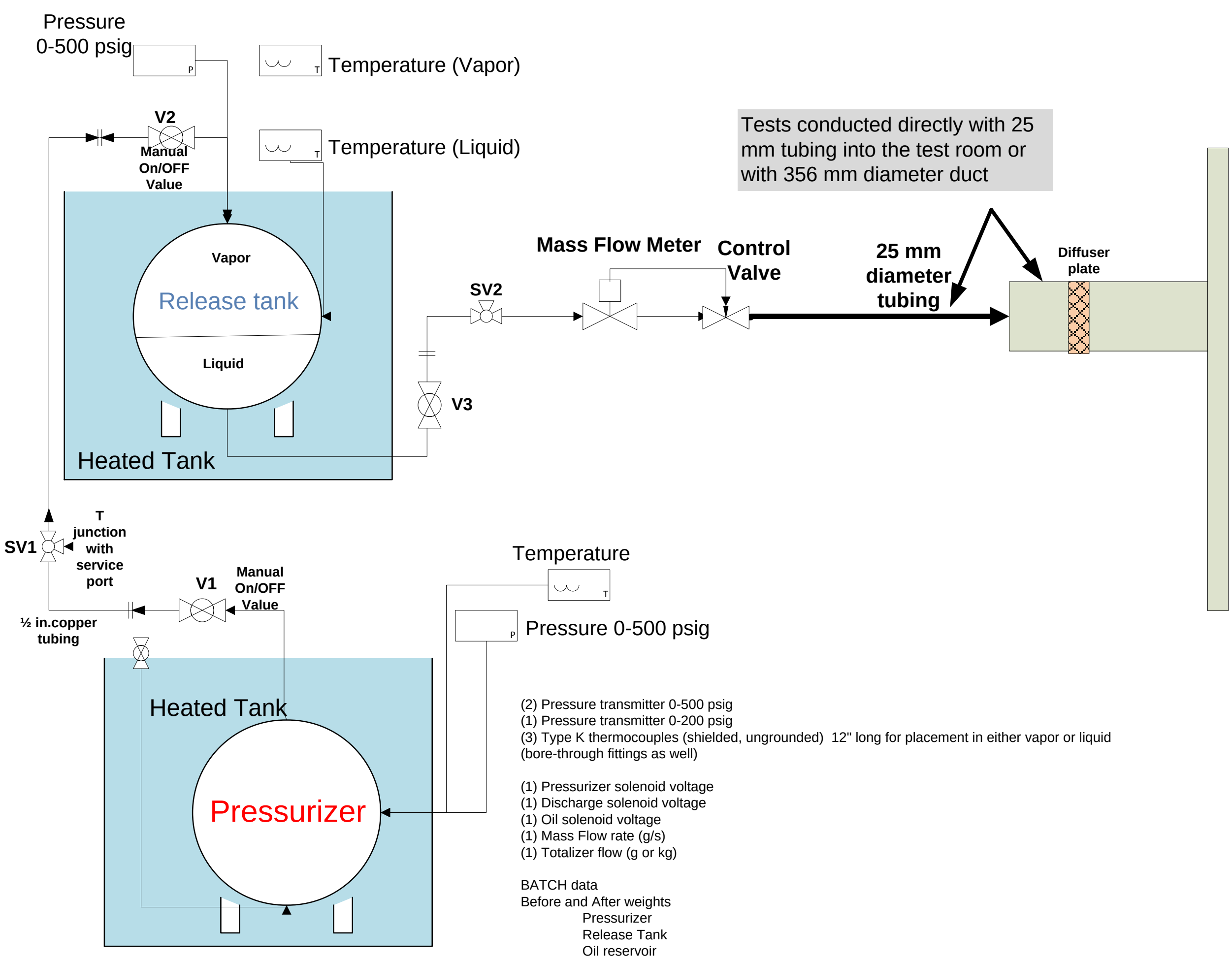


Figure 16 – Refrigerant release methodology without lubricating oil

For tests that included lubricating oil, the oil was mixed with the refrigerant between the mass flow meter and the control valve using a gear pump, as shown in Figure 17.

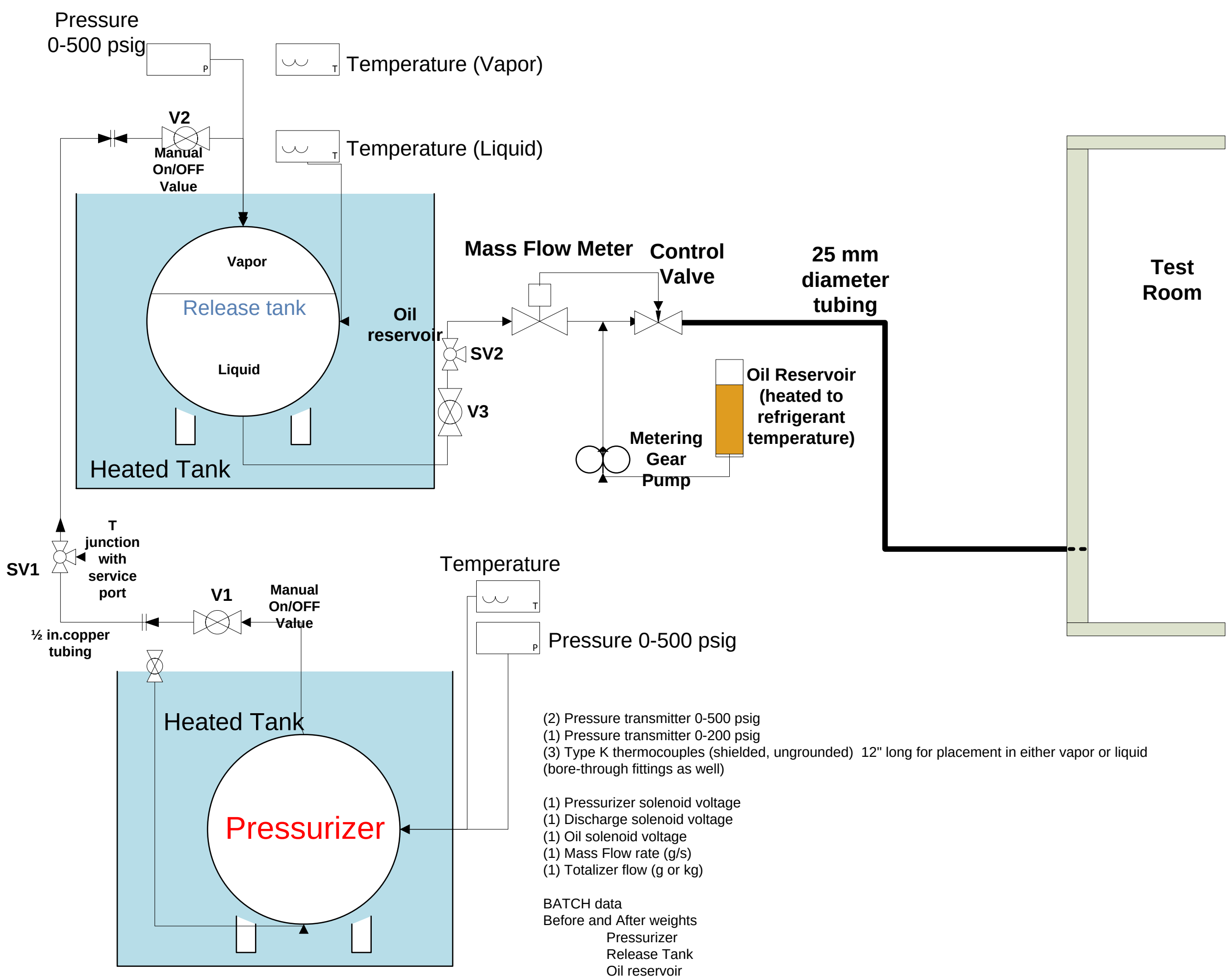


Figure 17 - Refrigerant release methodology with lubricating oil

Release of refrigerant into the room was achieved through two opening size diameters: (i) 1 in. (25 mm); and (ii) 14 in. (356 mm). For tests with 1 in. opening, the tube was directly connected to the test room; and for tests with 356 mm diameter opening, the release was passed through diffuser plates to reduce the refrigerant velocity and facilitate mixing before it entered the test room. These sizes were selected after discussions with AHRTI PMS. The length of the 1 inch copper tubing depending on the discharge location: approximately 1.8m for the 2.2 m height; 1.5 m for the 1.8 and 0.2 m heights. This same tubing was used to connect to the entrance to the 14 in. (356 mm) baffled duct section. sufficiently fast to drive turbulent mixing of the refrigerant with air, and the release from a large opening was slow enough that mixing with air was a buoyancy driven phenomenon.

It was anticipated that refrigerant release through a 1 in. diameter (smaller than CFD) tube would provide even a stronger jet (due to higher release velocity) and more mixing than observed from the

CFD analysis. The CFD analysis assumed vapor only discharge while the experimental observations noted that both liquid and vapor exited the 1 in. diameter tube.

The 25 mm diameter release was achieved using a 25 mm ID copper tube. The 356 mm diameter release was achieved using 14 in. diameter PVC duct sections assembled with three diffuser plates to mix the refrigerant before releasing it into the test room. Each diffuser plate was 0.125 in (3.2 mm) thick and had different holes and total open area. The duct assembly is depicted in Figure 18.

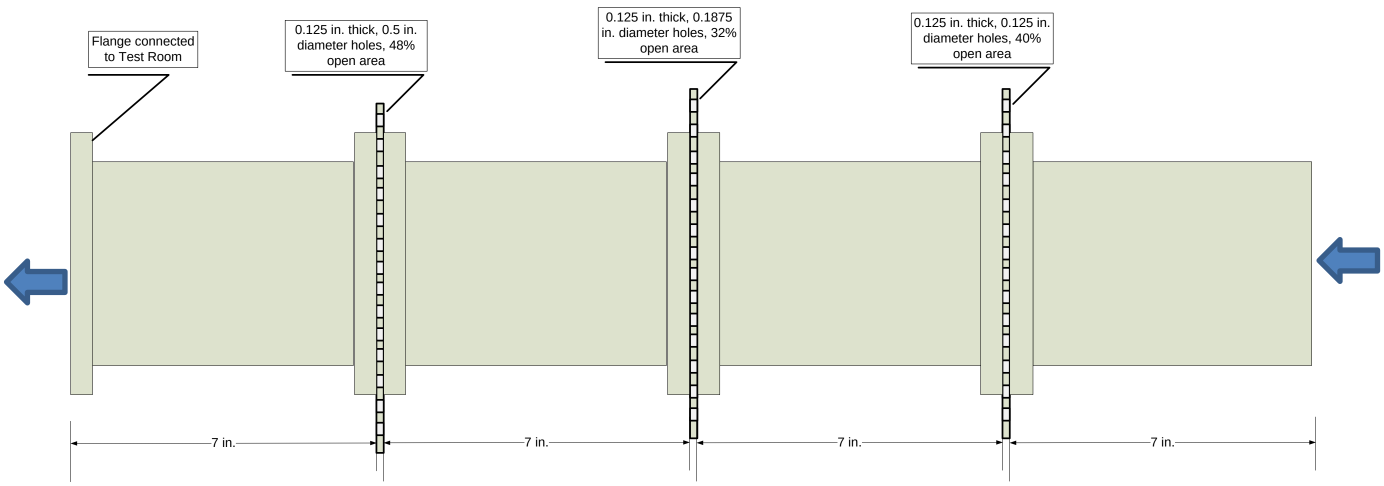


Figure 18 – 14 in. Release Duct Assembly

A photograph of the 14 in. duct assembly connected to the test room is shown in Figure 19.

Figure 19 – Photograph of the 14 in. Duct Assembly

These release opening sizes are slightly different from those used in the CFD simulations. The CFD results qualitatively demonstrated the critical differences between smaller and larger release openings with respect to refrigerant concentration buildup. The release velocity from a small opening was

3.2.4.1. Mass Flow Controller Response and Validation

The mass flow meter and controller were tested to develop response time characteristics and validation data for selected flows. The test set-up for response time and validation of the mass flow meter and controller is shown in Figure 20.

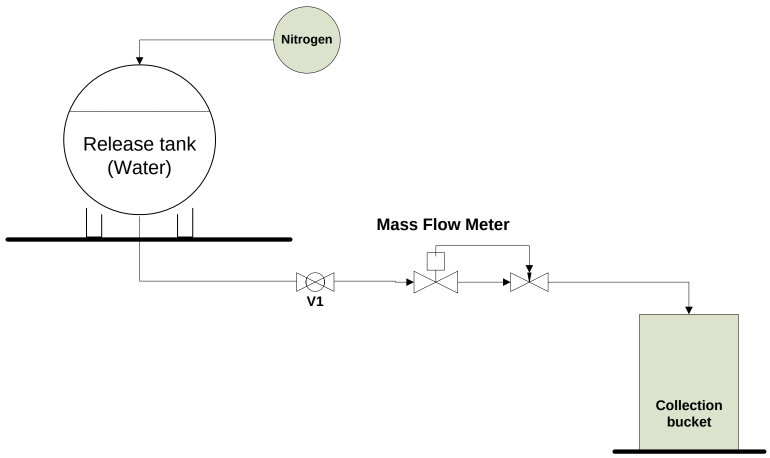


Figure 20 – Test Set up for Response Time and Validation of Mass Flow Meter and Controller

Tests were conducted with water for release rates between 5 and 111 g/s. Five tests were conducted for each flow rate used. The following procedure was used:

1. Fill the water tank with water and set the nitrogen pressure to 450 psi.
2. Weigh the empty collection bucket with a load cell.
3. Set the release rate by adjusting the mass flow controller.
4. Open valve V1, and collect water for a duration representative of the rate and time for refrigerant release.
5. Close valve V1.
6. Reweigh the collection bucket with load cell and calculate the total mass of water released.

A comparison between the mass of water measured with the collection bucket and calculation by the mass flow meter is shown in Table 7.

Table 7 – Validation Data for Mass Flow Meter and Controller

Mass Flow Rate (g/s)	Total Load cell (kg)	Total Mass Flow Controller (kg)	Error (kg)	% Error	Std. Deviation of % Error
5	3.20	3.25	0.05	1.56	1.89
5	3.05	3.25	0.20	6.56	
5	3.15	3.26	0.11	3.49	
5	3.20	3.26	0.06	1.87	
5	3.15	3.25	0.10	3.17	
13.5	3.15	3.25	0.10	3.17	0.82
13.5	3.15	3.27	0.12	3.81	
13.5	3.15	3.26	0.11	3.49	
13.5	3.20	3.27	0.07	2.19	
13.5	3.20	3.26	0.06	1.87	
50	3.05	3.13	0.08	2.62	0.61
50	3.20	3.29	0.09	2.81	
50	3.20	3.30	0.10	3.12	
50	3.15	3.26	0.11	3.49	
50	3.20	3.26	0.06	1.87	
75	3.25	3.38	0.13	4.00	2.04
75	3.30	3.44	0.14	4.24	
75	3.30	3.28	-0.02	-0.61	
75	3.25	3.38	0.13	4.00	
75	3.25	3.34	0.09	2.77	
100	3.75	3.84	0.09	2.40	0.68
100	3.15	3.28	0.13	4.13	
100	3.55	3.64	0.09	2.54	
100	3.20	3.34	0.14	4.37	
100	3.20	3.31	0.11	3.44	
111 [1]	3.25	3.37	0.12	3.69	0.55
111	3.20	3.32	0.12	3.75	
111	3.15	3.27	0.12	3.81	
111	3.55	3.70	0.15	4.23	
111	3.20	3.30	0.10	3.12	

Note: [1] Max value available with the mass flow meter

The total weight of water at the end of each test measured by a calibrated load cell was compared with the results with the mass flow controller as presented in Figure 21.

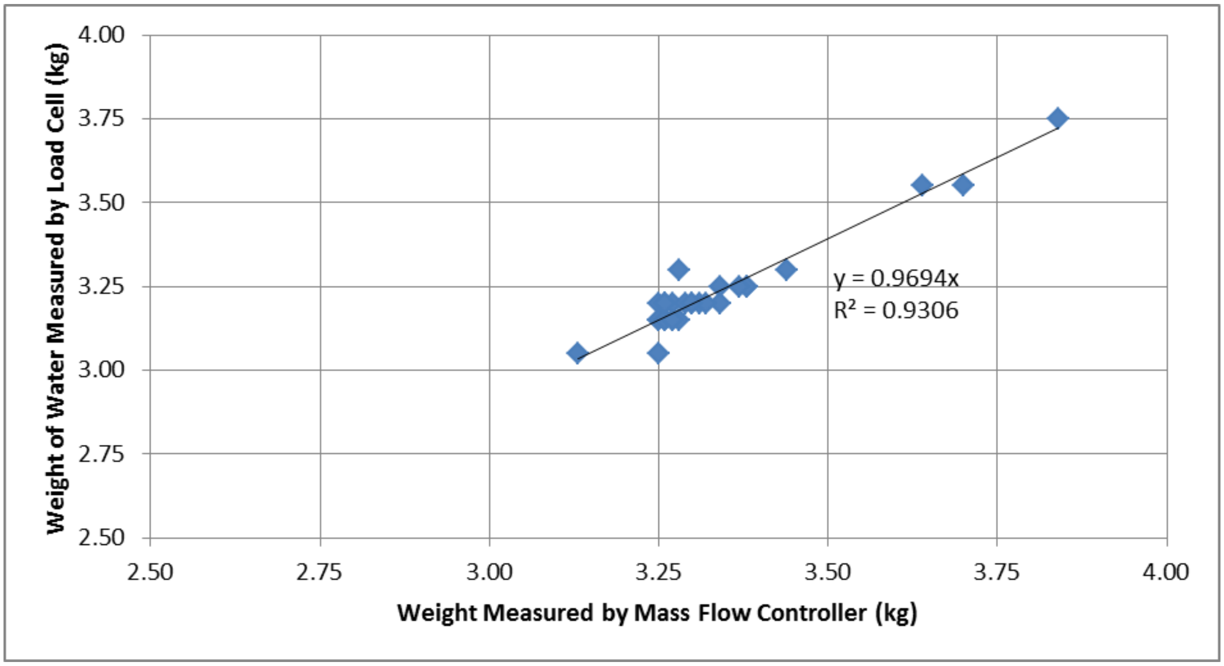


Figure 21 - Mass flow Controller Versus Load Cell

Figure 22 and Figure 23 show the % Error plotted against Total Mass Discharged and the Nominal flow rate, respectively. Included in each figure is a 95% prediction interval.

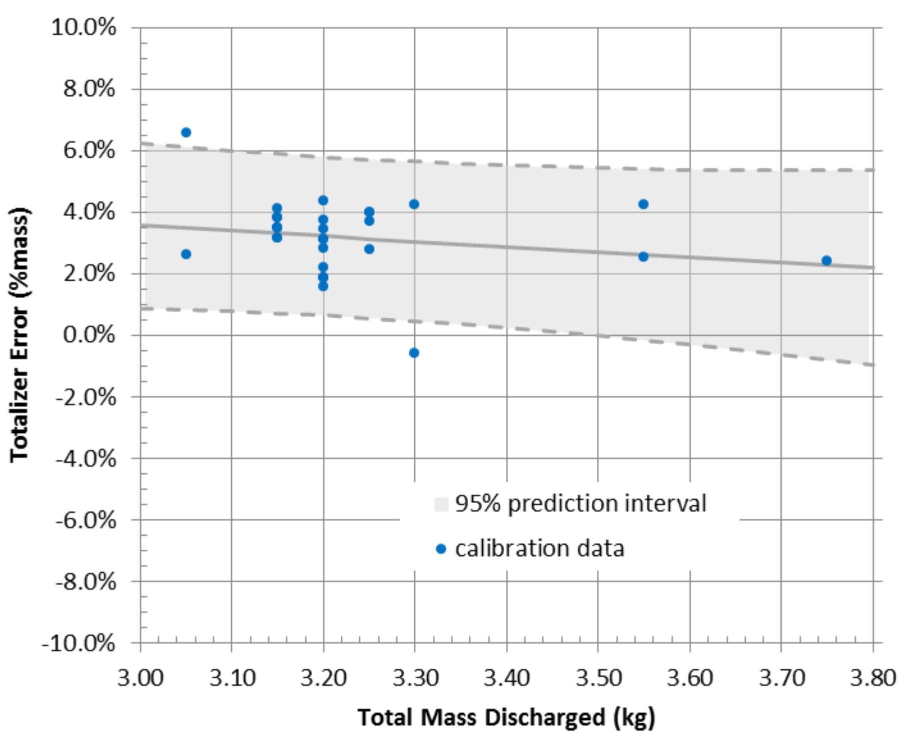


Figure 22 – Totalizer Error versus Total Mass Discharged

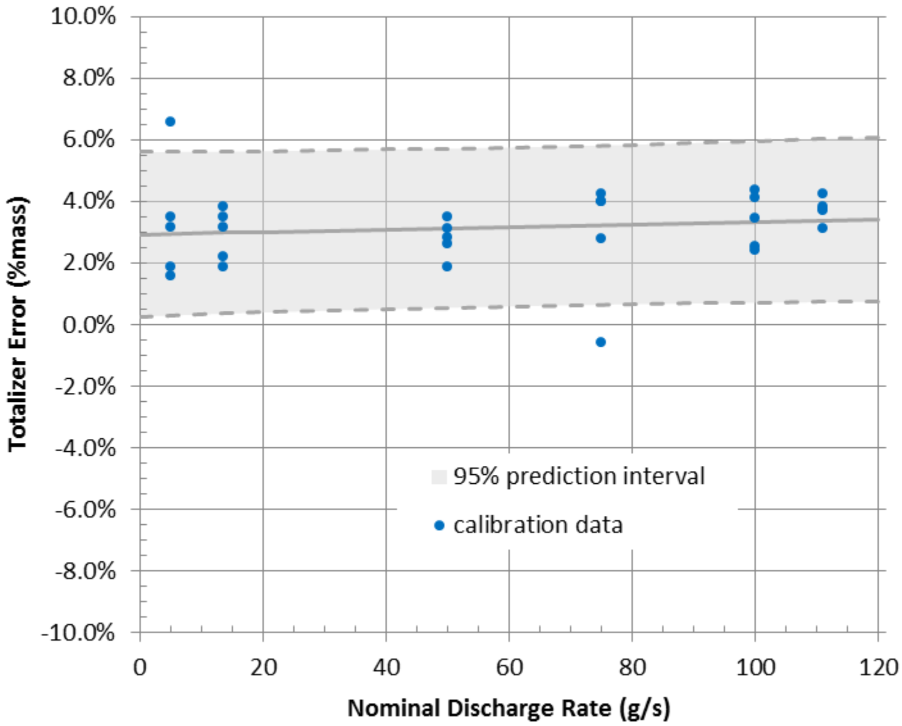
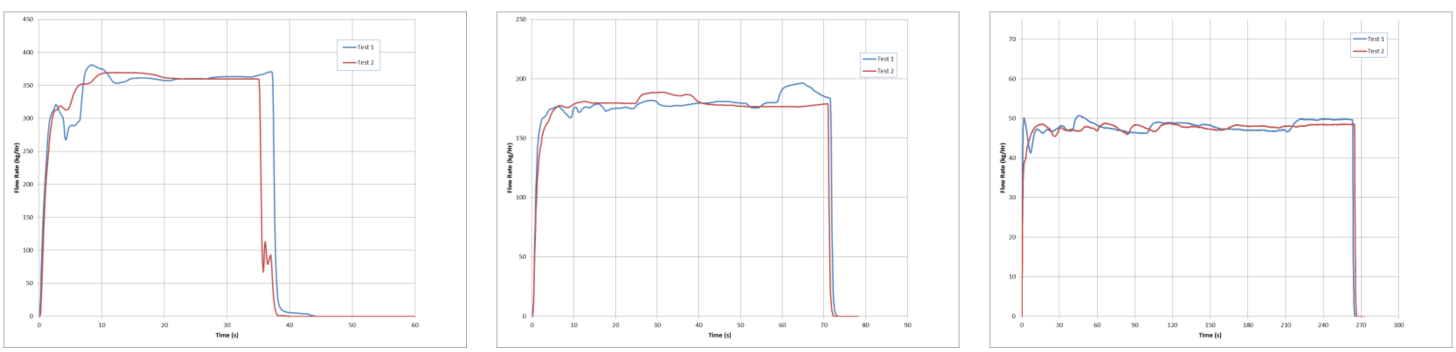


Figure 23 –Totalizer Error versus Nominal Discharge Rate

An approximate average bias of +3% was observed with the mass flow controller across the range of discharge rates. Since the bias is within the manufacturing specifications, the data collected during testing were not adjusted for the bias.

Figure 24 shows the response time of the mass flow controller to achieve the set release rate, for two trials at three release rates.



Release rate: 100 g/s   Release rate: 50 g/s   Release rate: 13.3 g/s

Figure 24 – Mass Flow Controller Response Time

It was found that the mass flow controller develops flow to the set release rate within 2 s for 100 g/s rate. This time is shorter for lower release rates.

3.2.4.2. Refrigerant Concentration Sensor Response Time and Calibration

3.2.4.2.1. Test Procedure

Each of four refrigerant concentration sensors used in the Task 1 experiments was attached to its respective central processing unit using the supplied cable.

A method to sample 100% by volume concentrations of each refrigerant or blend was constructed as follows: One side of the sampling port of each sensor was connected via an adjustable flow meter to a manifold of a vacuum pump. The flow meters were adjusted such that there was a constant volumetric flow of 1 Liter/minute at the inlet of all meters.

For refrigerants that are a blend: a sample of liquid refrigerant was placed inside another vessel and allowed to come to room temperature. The mass transferred into the sample cylinder was such that at room temperature all of the refrigerant would be vapor. For pure fluids the sample was taken from the vapor side of the tank.

Figure 25 shows the arrangement of the refrigerant tank, vented manifold, sample tubes, sensors, flowmeters, needle valves, and the sample pump. All sample tubes were the same length. When calibrating the sensors, the flow from the refrigerant tank was adjusted such that outflow was observed from the manifold vent. This flow insured that only calibration gas was flowing to the refrigerant sensors.

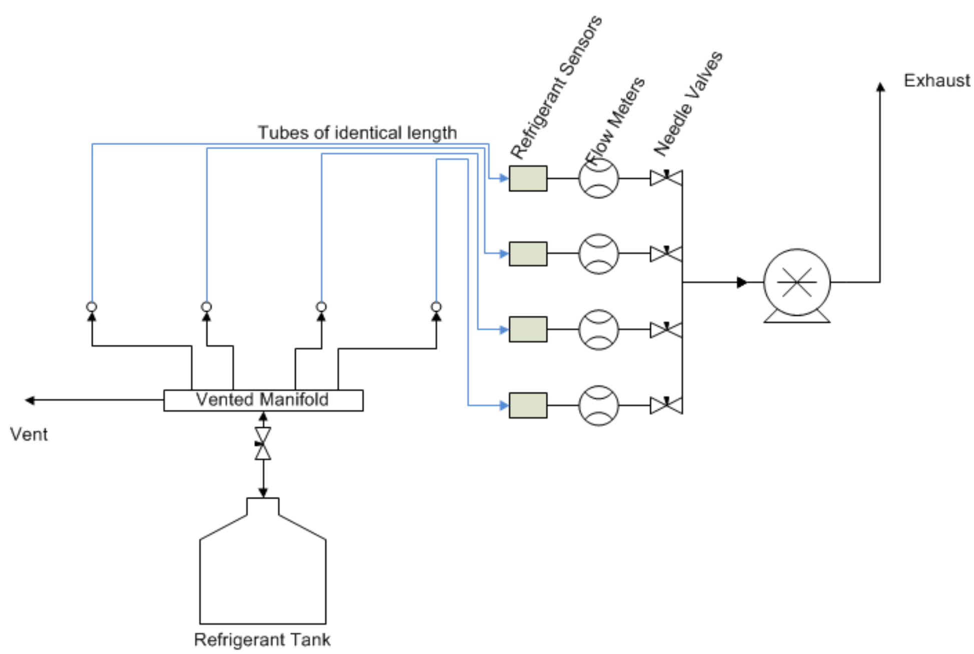


Figure 25 – Setup for calibration of refrigerant sensors

The vapor port of the sample cylinder was connected to a long tube that terminated at a manifold. One end of the manifold was vented to atmosphere. The other four manifold ports were connected to the inlets of the sensors at the start of the calibration test. This ensured that the sensors were not pressurized by the gas, but instead continued to draw the sample through the sensor at the rate that was controlled by the flow meter and sample pump. The length of the tube was sufficiently long allowing the refrigerant to warm to ambient temperature before reaching the sensor.

For each sensor, a recording of the output of the sensor [mV] was started in order to establish a baseline at ambient conditions. The valve on the refrigerant tank was then opened and the refrigerant was allowed to be pulled into the sensors. The output signal from the sensor was recorded until consistent readings were obtained. The sensor output voltage had a linear response to the concentration of the refrigerant. A linear least squares regression was conducted to determine an equation for percent refrigerant by volume as a function ($y = mx + b$) of sensor voltage.

The calibration results were also used to analyze the response time of the sensors to the different refrigerants. It was found that the response to step change in refrigerant concentration could be fitted with an exponential function. This enabled determination of response time constants.

3.2.4.2.2. Results

Selected calibration data for the sensors and refrigerants are presented in Table 8. Recalibrations were required for changes in sample tube length. The full set of calibrations are shown in Appendix F Refrigerant Sensor Calibrations. In the table, the refrigerant sensors are referred to as THCn23, THCn24, THCn25, and THCn26. The transport delay is the time taken from the sampling point to the sensors. The constants m and b were derived using linear least squares regression method.

Table 8 – Calibration Results for Refrigerant Sensors

Sensor	Refrigerant	m	b	Time Constant (s)	Transport delay (s) [1]
THCn23	R-22	-699.8	9.998	55	11
THCn24	R-22	-698.1	15.405	53	11
THCn25	R-22	-666.6	4.059	52	11
THCn26	R-22	-644.5	11.957	51	11
THCn23	R-32	-921.3	13.081	55	20
THCn24	R-32	-919.3	19.995	53	20
THCn25	R-32	-881.0	5.441	52	20
THCn26	R-32	-852.5	15.772	52	20
THCn23	R-410A	-1015.3	14.361	52	11
THCn24	R-410A	-1013.0	21.990	50	11
THCn25	R-410A	-970.3	5.939	49	11
THCn26	R-410A	-939.4	17.310	48	11
THCn23	R-452B	-979.4	13.931	56	11
THCn24	R-452B	-977.2	21.281	55	11
THCn25	R-452B	-936.4	5.799	53	11
THCn26	R-452B	-906.6	16.781	53	11
THCn23	R-455A	-1098.9	16.333	52	20
THCn24	R-455A	-1095.7	24.312	51	20
THCn25	R-455A	-1053.4	6.782	48	20
THCn26	R-455A	-1020.0	19.476	51	20
THCn23	R-457A	-1071.0	15.821	53	20
THCn24	R-457A	-1068.0	23.663	51	20
THCn25	R-457A	-1028.1	6.545	48	20
THCn26	R-457A	-994.6	18.907	51	20

Note: [1] The transport delay times were measured at various times during the test program. Details are presented in Appendix F Refrigerant Sensor Calibrations. The transport delay time increased during the test program because of the need to protect electrical connections from HF acid attack. This required removing the sensors from the test room resulting in longer runs of sample tubing to the sensors.

The time constant, and transport delay were used to calculate the instantaneous refrigerant concentration. An example of the deconvolution calculation to develop instantaneous concentration is presented in Figure 26.

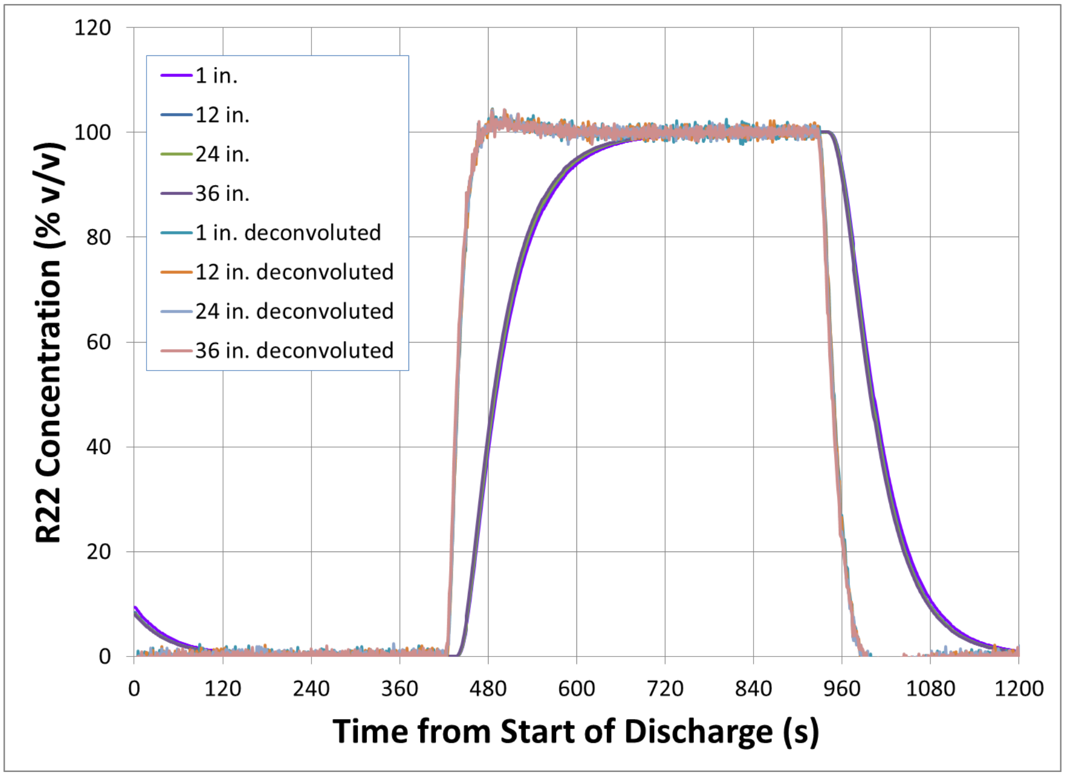


Figure 26 – Accounting for Refrigerant Sensor Response Time and Transport Delay

An additional example of deconvolution is shown in Figure 27. The data on the blue line shows the concentrations obtained from applying the slope and intercept values (m and b) from Table 8 using manually mixed concentrations of air and refrigerant of 0%, 15%, and 40%. Because the concentrations were manually mixed, there was a gradual change from one concentration to the next that took about 1 minute to establish. The red line shows the deconvolution of the blue line data.

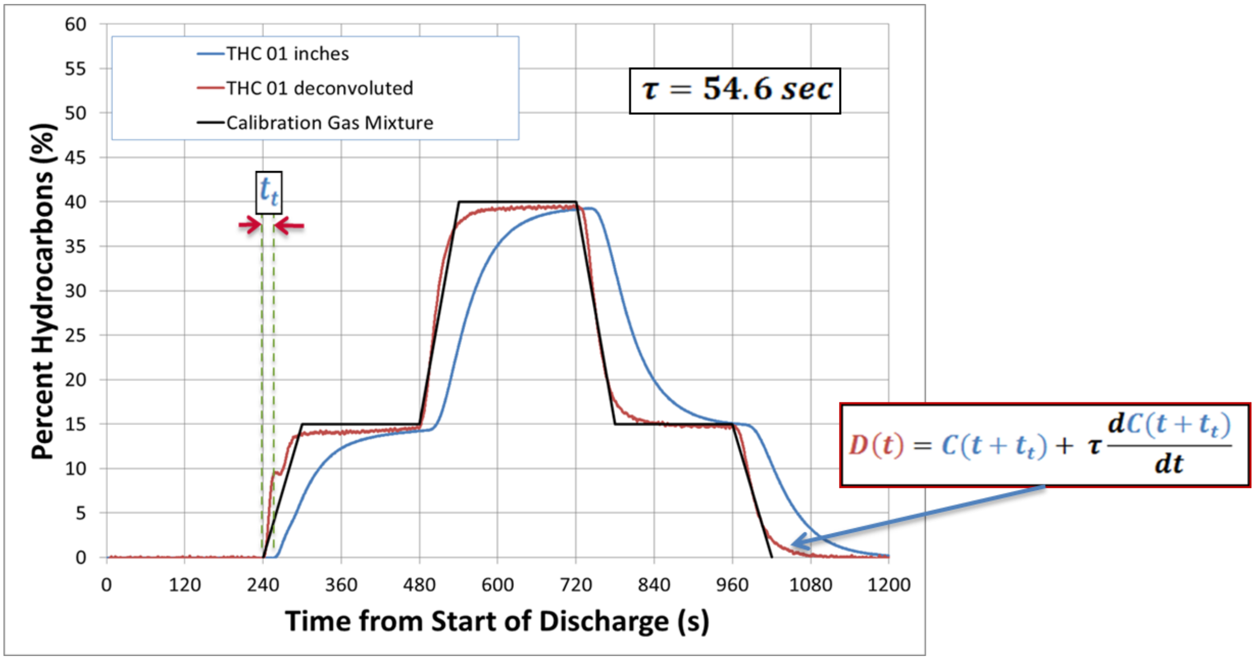


Figure 27 – Deconvolution test at 0%, 15%, and 40% concentrations

The terms in the deconvolution equation are as follows:

$D(t)$	The deconvolution data at time t in (% volume fraction)
$C(t + t_t)$	The concentration at time t plus the transport delay (% volume fraction)
τ	The exponential time constant (seconds)
$\frac{dC(t + t_t)}{dt}$	The rate of change of concentration at time t plus the transport delay (%/second)

3.2.4.2.3. Assumptions and Limitations of Deconvolution

Two simplifying assumptions were made in this application of deconvolution as follows:

- The flow of refrigerant through the sample line did not involve any mixing during transport (in other words – slug flow), and
- The response of the refrigerant sensor was an exponential response to a change in concentration. This exponential response was validated from the calibration data.

The assumption of exponential response is well supported by the data shown in Figure 26 and Figure 27. On the other hand, the assumption of slug flow is a simplification. In actuality, there is some mixing in the sample line. This mixing leads to blurring of the peaks and valleys of concentration.

3.2.5. Characterization of Test Room Leakage

A test was conducted using R-410A refrigerant to characterize the leak rate in the test room at the recommendation of AHRTI PMS.

3.2.5.1. Test Set-up

The test was conducted in the test room with a release rate of 100 g/s through a 25 mm opening located at a height of 2.2 m. The refrigerant used was R-410A. An electric fan was set up in the room to circulate and mix the refrigerant after it was released, and to enable a well-mixed assumption. The refrigerant sensors were located at 1, 3, 5, and 7 ft. (0.3, 0.9, 1.5, 2.1 m) from the floor and 3 ft. (0.91 m) from the release wall, and 18 in. (0.46 m) from side wall. A schematic of the test set-up is shown in Figure 28.

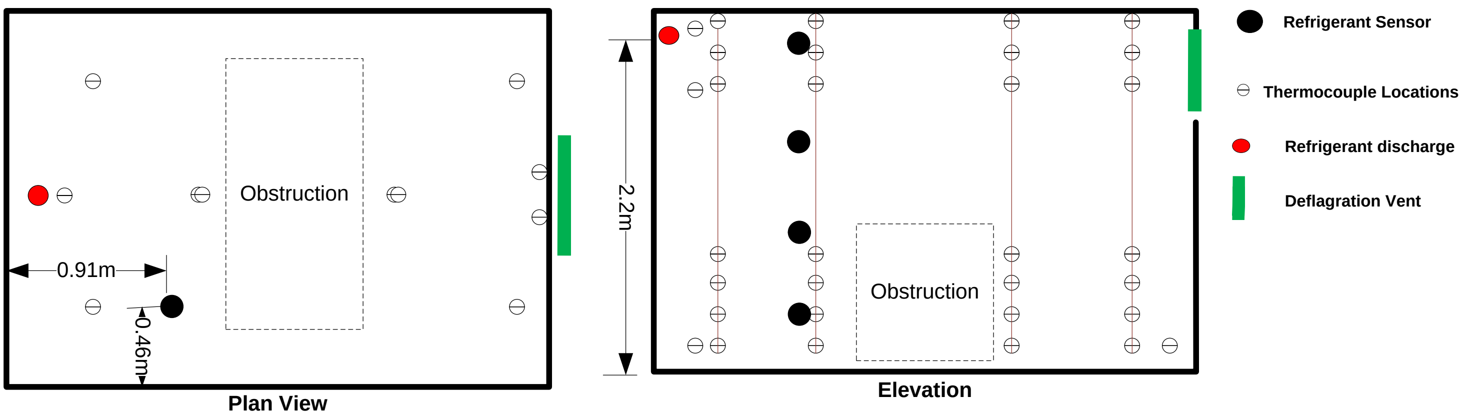


Figure 28 – Test Room Leakage Characterization

3.2.5.2. Test Procedure

In Test Cal15, refrigerant R-410A was released into the room at 100 g/s at a height of 2.2m through the 1 in. (25 mm) release opening. The total refrigerant release quantity was 5.21 kg which if uniformly distributed in the test room would yield a concentration of 8.3% v/v. This provided a refrigerant concentration (when well-mixed) sufficient to analyze leakage from the test room. The following test procedure was used:

1. Initiate the data acquisition, and video capture.
2. Open the pressurizer tank valve, and then the release tank valve, followed by opening the release valve to start refrigerant release into the test room.
3. Close the release valve, and switch on the electric fan to facilitate circulation and mixing.
4. After 1hr20 min (4,769 seconds), open the deflagration vent, and continue to collect refrigerant concentration data.
5. After 1hr 50 min (6,529 seconds), begin ventilation of the test room.
6. Stop data acquisition after 2 hours and 30 minutes after start of the refrigerant release.

3.2.5.3. Results

The refrigerant concentration is presented in Figure 29 and shows that the refrigerant was well-mixed in the room. The refrigerant sensor at the 7 ft. level had stopped functioning just prior to conducting this test.

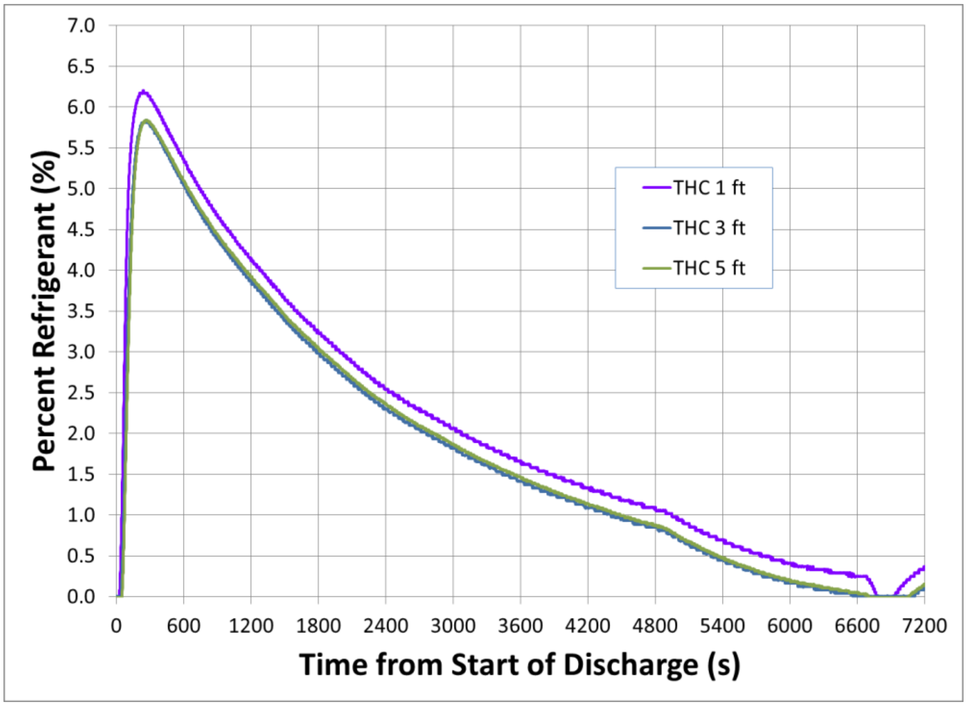


Figure 29 – Refrigerant Concentration: Leakage Test

The first 240 seconds of deconvoluted concentrations are shown in Figure 30. The data shows that peak concentrations climbed to levels above the expected 8.3% value due to the injection of refrigerant into the room. This was followed by mixing within the room and gradual convergence to a long term decay rate with nearly identical concentrations at every level.

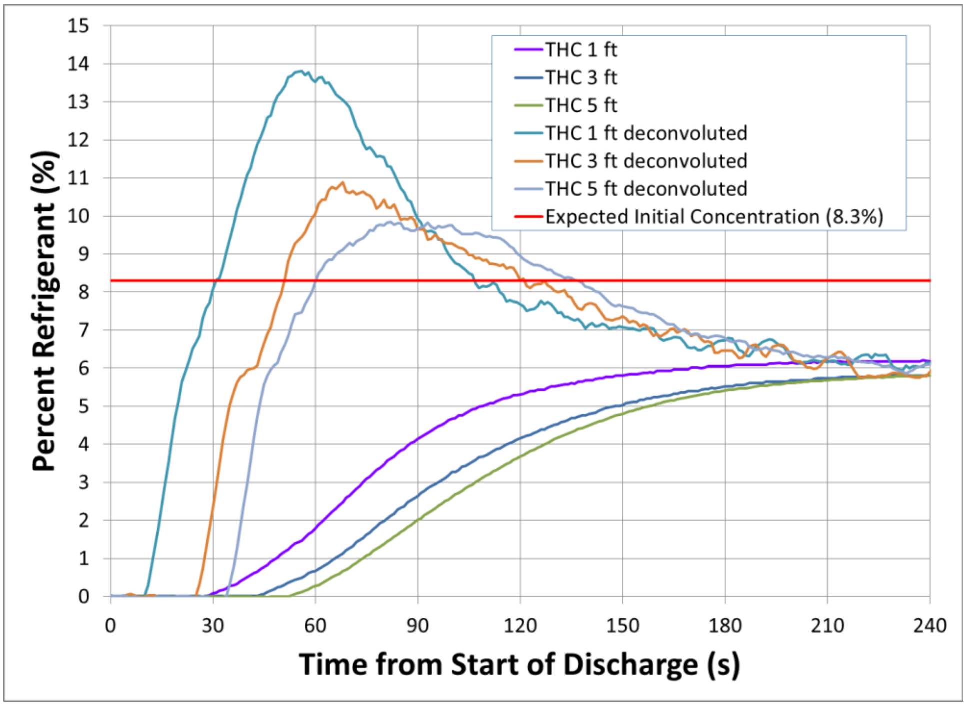


Figure 30 – Deconvoluted concentrations for the room leakage test

The leakage rate of the test room was determined by calculating the time constant of the slowly decaying refrigerant concentration. The deflagration vent in this test was the larger design used for Cal10 and throughout with the sliding window noted in section "3.2.1 Test Facility and Test Structure."

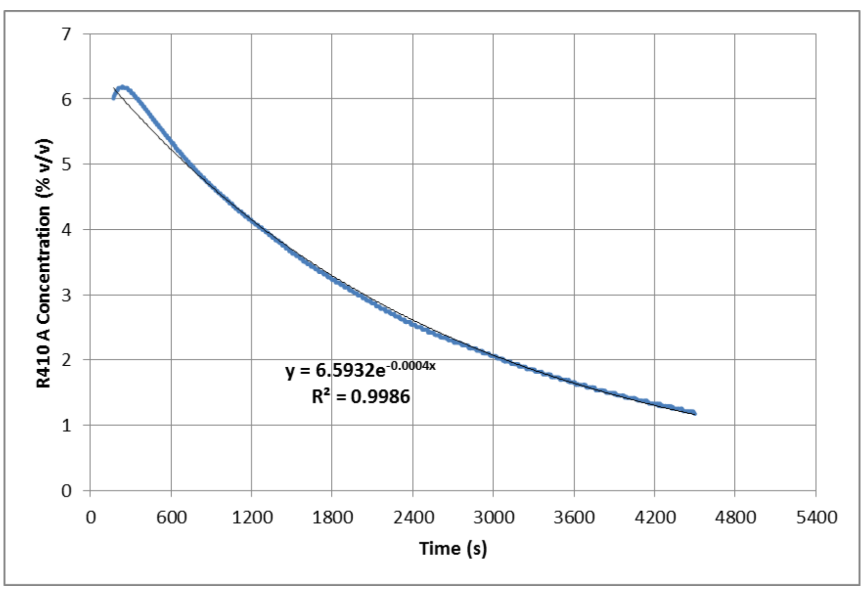


Figure 31 – Refrigerant Concentration Decay with Deflagration Vent Closed

Figure 31 shows that the refrigerant concentration decay, starting from peak value, in the test room is exponential with a time constant of 2500 s (calculated from τ = 1/0.0004 s). When the deflagration vent is opened, the concentration decay rate increases with a time constant of 1250 s (calculated from τ = 1/0.0008 s) as shown in Figure 32.

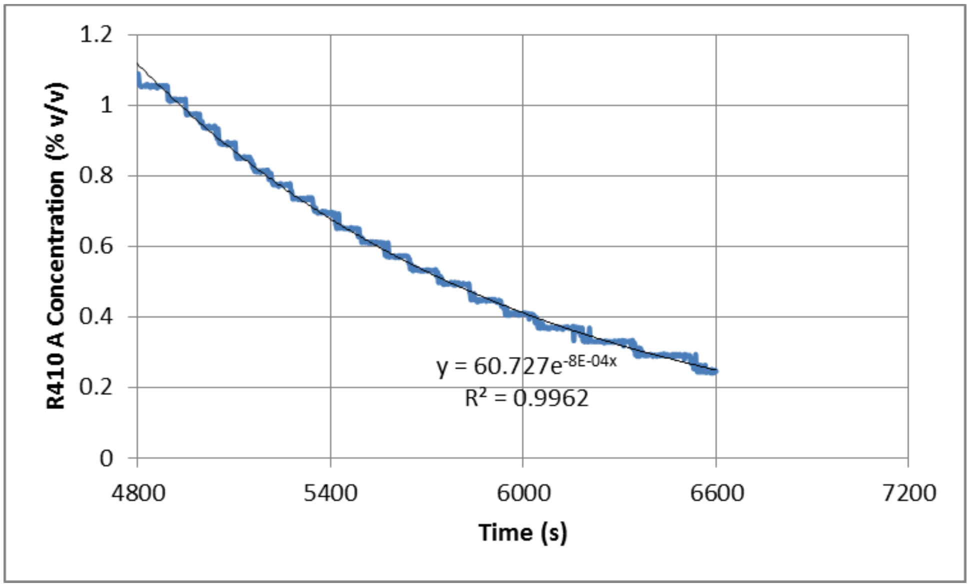


Figure 32 - Refrigerant Concentration Decay with Deflagration Vent Open

3.3. Calibration Testing

3.3.1. Room Tests

Eighteen calibration tests were conducted in the test room to investigate the influence of (i) refrigerant release rates; (ii) the vertical location of the release; and (iii) release opening size on the potential for ignition for two class A2L refrigerants. The results of these tests were used to identify the release rate, location and opening size that provide the highest (among these tests) ignition potential and fire hazard. These tests were conducted with the test room conditioned to 91±3 °F and 70±5 % RH. R-32 refrigerant (LFL = 14.4 vol%) was selected due to its higher burning velocity. Electric arcs were used as ignition sources. A calibration matrix was developed with the following variables:

- Refrigerant release rate: 100 g/s, 50 g/s, and 13.5 g/s.
- Refrigerant release location: 0.2 m, 1.8 m, and 2.2 m height
- Refrigerant release opening: 25 mm, 356 mm diameter (1 in and 14 in.)

The matrix of tests conducted in the Calibration Test Series is presented in Table 9.

Table 9: Calibration Test Series Matrix

Test #	Refrigerant	Release rate (g/s)	Release location (m)	Opening diameter (mm)	Target percent of LFL concentration (%)
Cal01	R-32	100	2.2	25	50
Cal02	R-32	100	2.2	25	50
Cal03	R-32	100	2.2	25	50
Cal04	R-32	100	2.2	25	50
Cal05	R-32	13.5	2.2	25	50
Cal06	R-32	100	2.2	25	50
Cal07	R-32	13.5	0.2	25	50
Cal08	R-32	100	0.2	25	50
Cal09	R-32	100	0.2	25	50
Cal10	R-32	13.5	0.2	356	50
Cal11	R-32	100	0.2	356	50
Cal12	R-32	13.5	2.2	356	50
Cal13	R-32	100	2.2	356	50
Cal14	R-410A	100	2.2	25	50
Cal15	R-410A	100	2.2	25	50
Cal16	R-32	50	1.8	25	50
Cal17	R-32	50	1.8	356	50
Cal18	R-452B	100	0.2	25	50
Cal19	R-32	100	2.2	356	25
Cal20	R-32	100	2.2	356	25

Tests Cal01 through Cal04 verified the refrigerant delivery, refrigerant sensors, and electric arc ignition systems. These tests are not reported in the Technical Report.

The calibration test series starts from Cal05 after shakedown tests for equipment and procedures were completed. Cal14 and Cal15 measured the leakage in the test room. Cal14 was repeated due to malfunction of instrumentation and is not reported in the Technical Report. Results from Cal15 were discussed in the section "Characterization of Test Room Leakage".

Tests Cal05 through Cal17 developed data on the influence of refrigerant release rate, release height and opening diameter. A schematic of the test matrix with the three test parameters is shown in Figure 33. The vertices of the matrix are: 1) 0.2 or 2.2 m Release Height; 2) 25 or 356 mm Release opening diameter; and 3) 13.5 or 100 g/s Release Rate. The red squares represent the midpoint tests at the 1.8 m height, 50 g/s, and either 25 or 356 mm opening diameter.

Cal19 and Cal20 were added during the Parametric Testing for evaluation of a discharge equivalent to 25% of the R-32 LFL. Cal19 is not reported due to a failure of the data acquisition system 30 seconds after the start of the test.

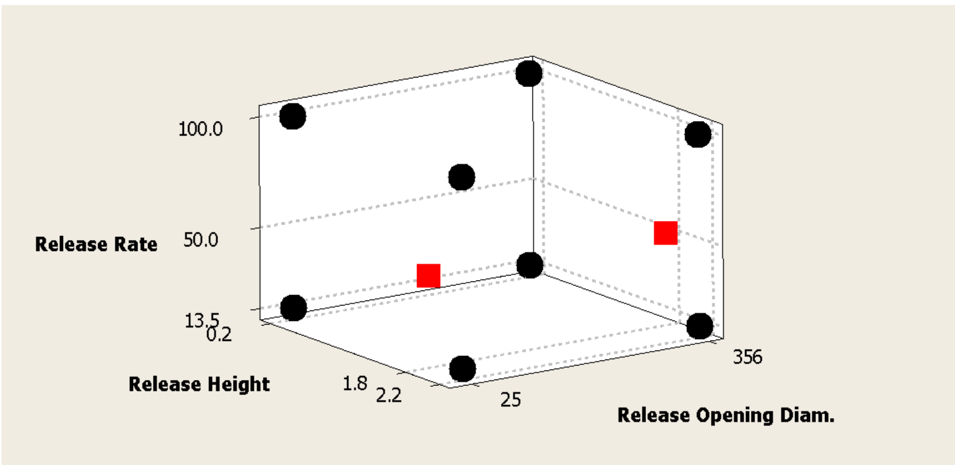


Figure 33 – Test Matrix. The red squares are on the 25 and 356 mm Release Opening Diameter face of the cube.

3.3.2. Instrumentation

The location of thermocouples, electric arc igniters and refrigerant concentration sensors are shown in Figure 34 and listed with dimensional detail in Table 10.

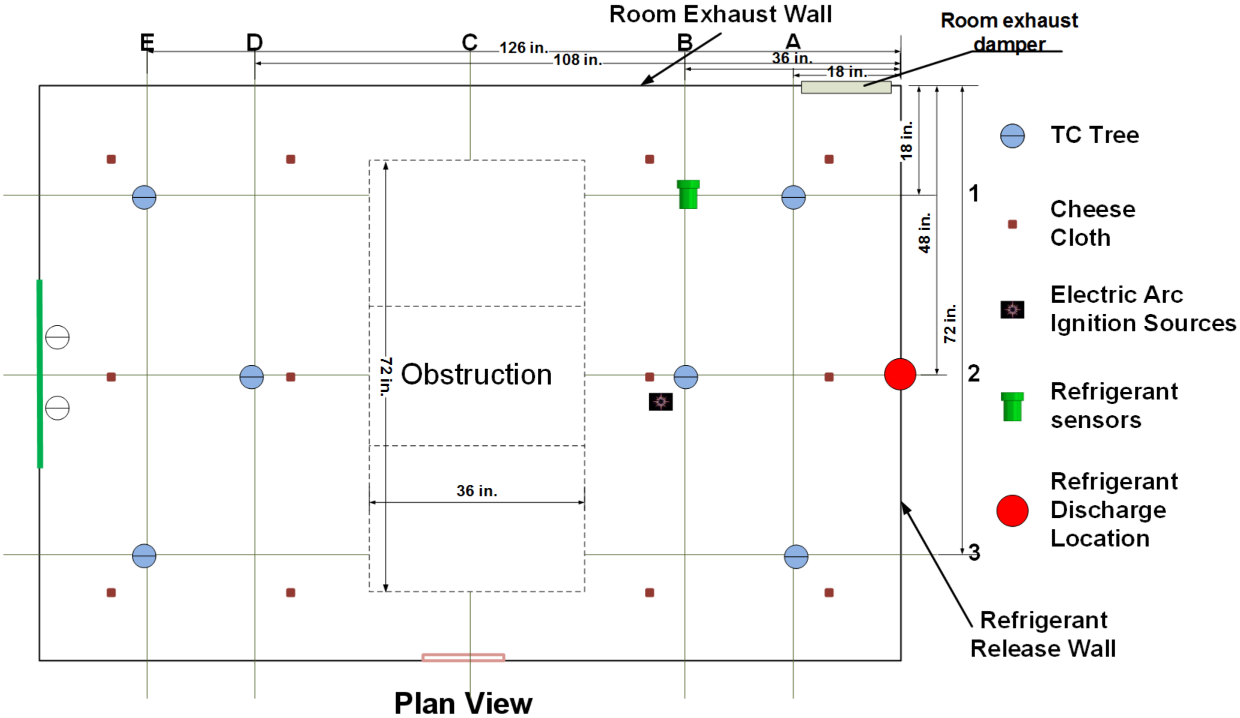


Figure 34 – Task 1 Instrumentation Plan

Table 10 – Calibration Tests - Location of Instrumentation and Electric arcs

Instrumentation Location	Distance from Refrigerant Release Wall (in.)	Distance from Room Exhaust Wall (in.)
A1	18	18
A3	18	72
B2	36	48
D2	108	48
E1	126	18
E3	126	72

The refrigerant sensors were positioned at Location B1 and vertically positioned 1 in., 12 in., 24 in., and 36 in. (0.03 m, 0.30 m, 0.60 m, 0.91 m) above the floor; the electric arcs were positioned at Location B2 in a tree assembly at 1 in., 12 in., 24 in., and 36 in. (0.04 m, 0.30 m, 0.60 m, 0.91 m)above the floor; and the thermocouples were at Locations A1, A3, B2, D2, E1, and E3 and at 4 in., 8 in., 12 in., 18 in., 60 in., 84 in., 88 in. and 92 in. (0.10 m, 0.20 m, 0.30 m, 0.46 m, 1.52 m, 2.13 m, 2.24 m, 2.34 m) above the floor.

3.3.3. Test Procedure

The following procedure was used to conduct each test starting from Cal05. These procedures were developed during the shakedown tests in Cal01 through Cal04:

1. Confirm pressure and release tank pressure and temperatures.
2. Confirm the test room temperature and humidity were 91 °F ± 3 °F and 70 % RH ± 5 % RH.
3. Initiate data acquisition and video capture 1 minute prior to discharging refrigerant.
4. Develop vacuum (less than 1 mm Hg) in piping connecting the pressure and release tanks as well as between the release tank and flow meter.
5. Initiate data acquisition 60 s prior to release of refrigerant.
6. Open the valve between the pressure and release tanks, and hold for 5 s.
7. Open the valve between release tank and the flow meter and hold for 5 s.
8. Open the control valve to initiate refrigerant release through the mass flow meter.
9. For tests Cal01 through Cal09: Close the release tank valve when target quantity of refrigerant has been released; discontinue sampling of refrigerant through the refrigerant sensors, and initiate electric arcs.
   From Cal10 through Cal18: Close the release tank valve when target quantity of refrigerant has been released; discontinue sampling of refrigerant through the refrigerant sensors; open sliding deflagration door; and initiate electric arcs. (Note: The sliding deflagration door was added after Cal09)
10. Continue to collect data until all flaming has ceased for at least 2 minutes.
11. Vent the test room.

After each test, the test facility was exhausted through UL's smoke abatement system (RTO), and the conditions in the facility were monitored with open path gas FT-IR. Staff re-entered the test facility to set up the next test only after the gas FT-IR indicated normal ambient conditions.

3.3.4. Summary Results for Calibration Tests

A summary of the release rates in tests are presented in Table 11. The target quantity of refrigerant released for each test to achieve a concentration level equal to 50% LFL was 3.25 kg for R-32 and 3.36 kg for R-452B.

Table 11 – Summary of Refrigeration Release Rates

Test Number	Refrigerant	Target Release Rate (g/s)	Release Height (m)	Release Opening (mm)	Total Mass Released (kg)	Fully Mixed Percentage of LFL based on Mass Release (%)	Average Release Rate (g/s)
Cal05	R-32	13.5	2.2	25	3.26	50.2	13.6
Cal06	R-32	100	2.2	25	3.35	51.5	83.8
Cal07	R-32	13.5	0.2	25	3.25	50.0	13.8
Cal08	R-32	100	0.2	25	3.32	51.1	79.0
Cal09	R-32	100	0.2	25	3.34	51.4	81.6
Cal10	R-32	13.5	0.2	356	3.27	50.3	13.8
Cal11	R-32	100	0.2	356	3.29	50.6	80.3
Cal12	R-32	13.5	2.2	356	3.21	49.4	13.5
Cal13 [1]	R-32	100	2.2	356	3.26	50.2	55.2
Cal16	R-32	50	1.8	25	3.28	50.5	48.9
Cal17	R-32	50	1.8	356	3.30	50.8	49.2
Cal18	R-452B	100	0.2	25	3.46	53.2	93.4
Cal19	No Data						
Cal20	R-32	100	2.2	356	1.93	29.7	93.9

Note: [1] Pressure in the release tank dropped rapidly resulting in poor control of refrigerant release.

In this series of tests, it was difficult to achieve the target release rate of 100 g/s. Analysis of the test parameters (e.g., initial pressure in pressurizer and release tanks) showed that the release rate was sensitive to the initial refrigerant charge in the pressurizer and release tanks. An improved procedure increased the amount of refrigerant charge in the pressurizer tank. The improved procedure was employed in Parametric Test series. Cal19 was invalid due to equipment failure. The influence of refrigerant release quantity (Cal 20) was added to the scope after review of the calibration test results by the AHRTI Project Management Subcommittee (AHRTI PMS). Cal20 results are discussed in the section on parametric test results.

3.3.5. Discussion of Calibration Test Results

In the calibration tests, release rates (100 g/s , 50 g/s, and 13.3 g/s), release location (2.2 m, 1.8 m, and 0.2 m), and release openings (25 mm, 356 mm) were explored to determine which of these parameters develop conditions conducive to ignition and propagation. All the tests were conducted at a room temperature 91±3 °F, and 70±5 % RH with an obstruction.

3.3.5.1. Influence of Refrigerant Release Rate, Release Height, and Size of Opening

A summary of results with the 25 mm release opening are provided in Table 12. The deflagration vent was the original (smaller) vent in tests Cal05-Cal09. The larger deflagration vent was in place for all tests after Cal09.

Table 12 – Influence of Release Rate and Location (25 mm opening)

Test Number	Ave Release Rate (Target Release rate) (g/s)	Release Height (m)	Ignition or Event	Max Pressure (mm Hg)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)
Cal05	13.6 (13.5)	2.2	Ignition	0.664	336	243
Cal06	83.8 (100)	2.2	No Ignition	0.008	97	95
Cal07	13.8 (13.5)	0.2	Ignition	3.947	914	672
Cal08	79.0 (100)	0.2	Ignition	2.656	1458	1197
Cal09	81.6 (100)	0.2	Ignition	4.476	1241	882
Cal16	48.9 (50)	1.8	No Ignition	0.009	202	187

The maximum measured pressure occurred immediately after ignition.

Refrigerants with a release rate of 100 g/s at a height of 0.2 m resulted in ignition of the refrigerant mixture, whereas there was no ignition when released from a height of 2.2 m at this release rate. At the lower release location (0.2 m) and higher release rates (≥ 79.0 g/s), the obstruction appeared to facilitate mixing of the refrigerant with air to create a flammable mixture. For a slower release rate (13.8 g/s), the refrigerant pooled at the floor and created refrigerant-rich mixture that resulted in ignition. The results are graphically presented in Figure 35.

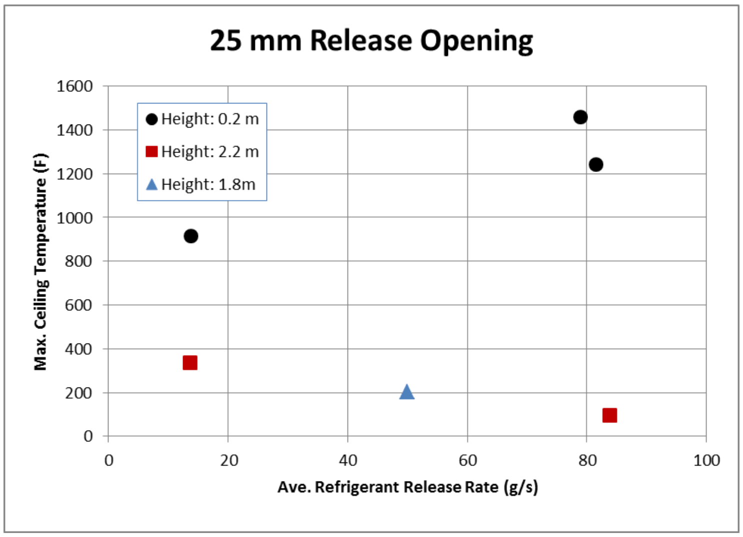


Figure 35 – Maximum Temperature Refrigerant Released from 25 mm diameter opening

Figure 36 shows the influence of refrigerant release rate on room temperatures at the B2 thermocouple array (the location proximate to the ignition sources) and refrigerant concentration from 0.2 m height and through a 25 mm diameter opening.

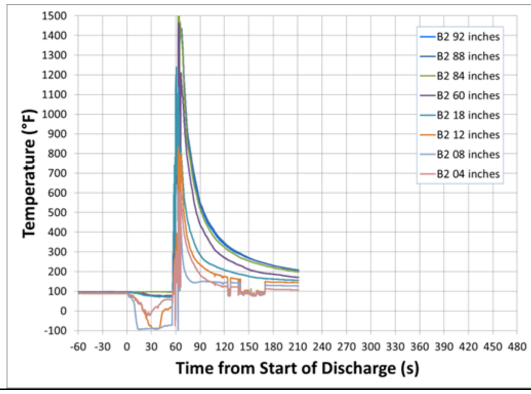
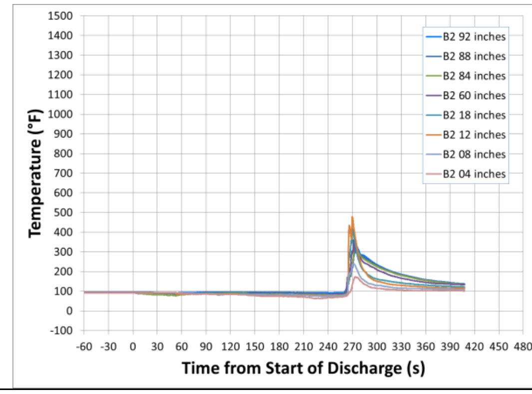
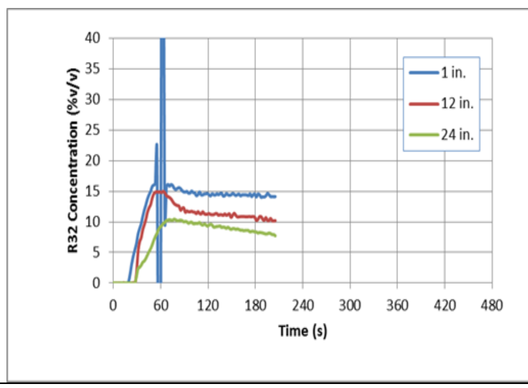
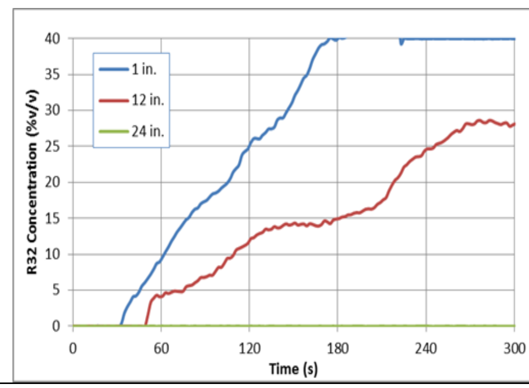
<table>
<tr><th>Measurement</th><th>100 g/s</th><th>13.5 g/s</th></tr>
<tr><td>Temperature (B2)</td><td>
</td><td>
</td></tr>
<tr><td>R-32 Concentration</td><td>
</td><td>
</td></tr>
</table>

Figure 36 – Influence of Refrigerant Release Rate (100 g/s from 0.2m height through a 25 mm diameter opening)

A comparison of the R-32 concentration plots (Figure 36) shows that there is more refrigerant gas pooling at the floor level for the lower release rate. This resulted in a smaller volume of flammable gas mixture and thus lower temperatures.

Release from a 2.2 m height at 100 g/s resulted in mixing of the refrigerant with ambient air in the room. This is observed from the concentrations measured by the sensors at 1 in., 12 in., and 24 in. heights. The mixing resulted in a refrigerant mixture below the LFL and no ignition event occurred. Release from the same height at a 13.5 g/s resulted in refrigerant pooling and ignition. The data are presented in Figure 37.

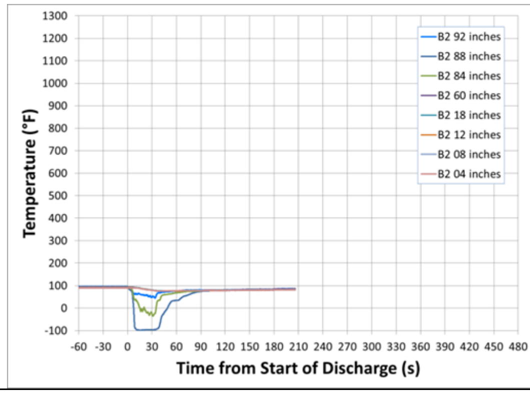
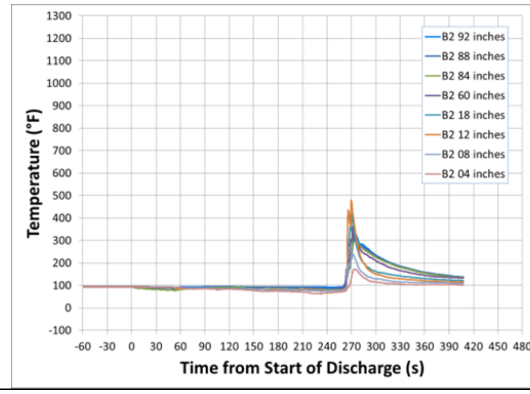
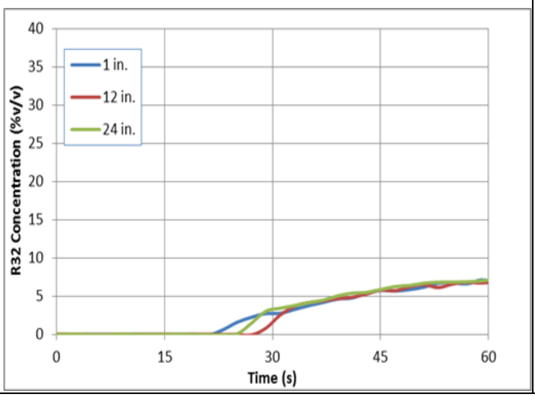
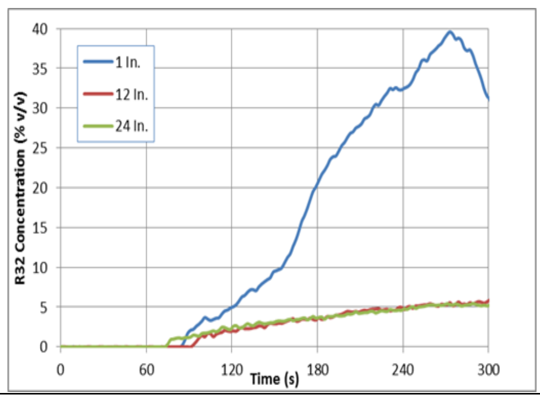
<table>
<tr><th>Measurement</th><th>100 g/s</th><th>13.5 g/s</th></tr>
<tr><td>Temperature (B2)</td><td>
</td><td>
</td></tr>
<tr><td>R-32 Conc.</td><td>
</td><td>
</td></tr>
</table>

Figure 37 - Influence of Refrigerant Release Rate
(100 g/s and 13.5 g/s from 2.2 m height through a 25 mm diameter opening)

A comparison of refrigerant concentrations at a release rate of 13.5 g/s in Figure 36 and Figure 37 show that refrigerant pooling at the floor occurs for release from both the 0.2 and 2.2 m heights.

A summary of results with refrigerant release from a 356 mm opening with baffling are presented in Table 13.

Table 13 - Influence of Release Rate and Location (356 mm opening with baffling)

Test Number	Release Rate (g/s)	Release Height (m)	Max Pressure (mm Hg)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)
Cal10	13.8	0.2	0.024	431	338
Cal11	80.3	0.2	0.040	498	367
Cal12	13.5	2.2	0.006	98	95
Cal13	55.2	2.2	0.338	1365	1094
Cal17	49.2	1.8	0.180	762	634

With the larger opening size, the refrigerant pooled to the bottom of the test room between the opening location and the obstruction irrespective of the release rate. Higher refrigerant release rates from the 356 mm opening resulted in higher maximum and average ceiling temperatures. Regardless of release rate, some refrigerant accumulated between the diffuser plates inside the 356 mm duct. This resulted in a lower total refrigerant release quantity into the test room. This phenomenon is shown in Figure 38 from test Cal17.

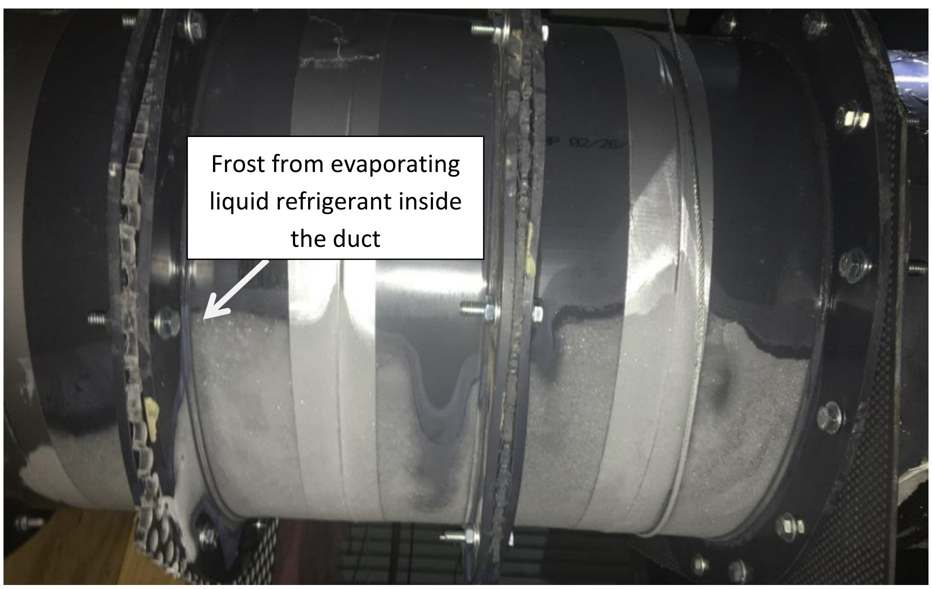


Figure 38 - Frost on the 356 mm Duct Indicating Presence of Residual Refrigerant in Duct

Maximum ceiling temperature results with release from the 356 mm diameter opening are presented graphically in Figure 39.

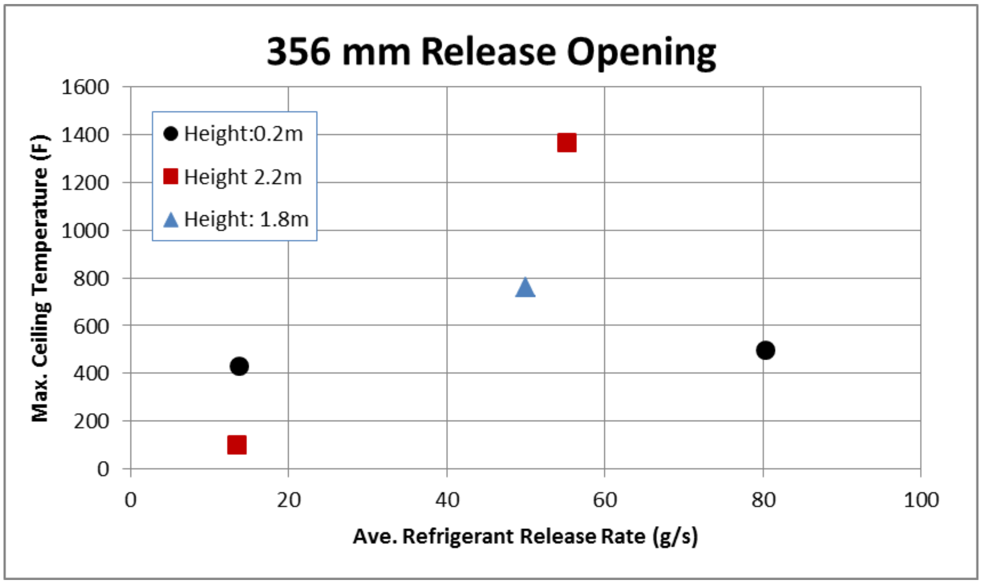


Figure 39 - Maximum Temperature Refrigerant Released from 356 mm diameter opening

The influence of the size of the refrigerant release opening is presented in Figure 40.

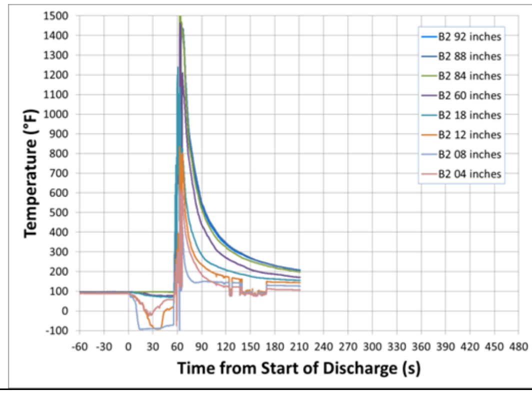
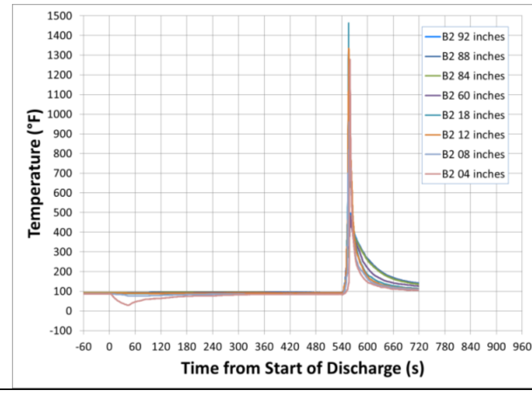
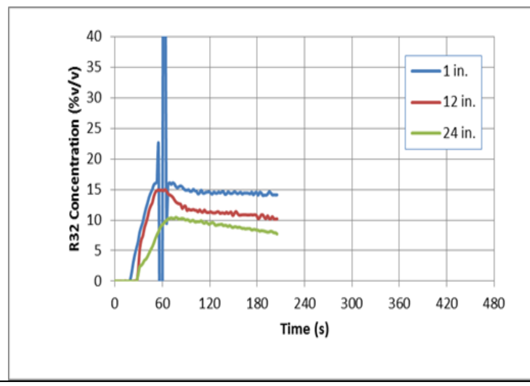
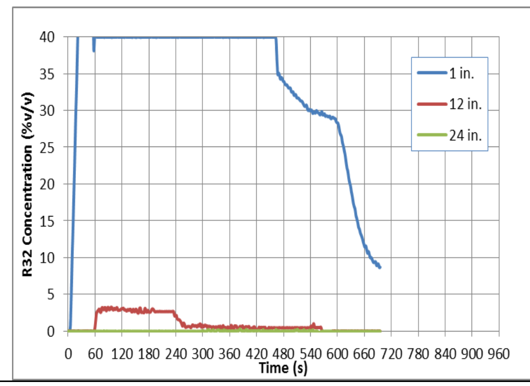
<table>
<tr><th>Measurement</th><th>25 mm diameter</th><th>356 mm diameter</th></tr>
<tr><td>Temperature</td><td>
</td><td>
</td></tr>
<tr><td>R-32 Conc.</td><td>
</td><td>
</td></tr>
</table>

Figure 40 – Influence of Refrigerant Release Opening Diameter (Release rate: 100 g/s; 0.2m height)

With the refrigerant release from 25 mm opening at 0.2m, the refrigerant jet impacted the obstruction and created localized flammable mixture that ignited.

The refrigerant concentration from a 356 mm opening at the 0.2 elevation was above the flammability limits at the 1 in. height, indicating pooling at the floor level. When the electric arcs were energized immediately after completion of the release there was no ignition due to the local concentration being higher than the UFL at the 1-inch level. The ignition of the gases occurred at a second attempt. A second ignition attempt was made after the concentration at the 1 in. height fell between upper and lower flammability limits, and resulted in ignition of the refrigerant mixture.

3.3.5.2. Comparison between R-32 and R-452B Refrigerants

Two tests were conducted with R-452B and R-32 refrigerants with a release rate of 100 g/s at a 0.2 m release height and through a 25 mm diameter opening and subsequent ignition. However, it should be noted that 100 g/s was the target release rate. The actual release rate for R-32 was about half of the release rate for R-452B. A comparison of results is presented in Table 14.

Table 14 – Comparison of R-452B vs. R-32 Results

Refrigerant	Test Number	Max Pressure (mm Hg)	Refrigerant Release Rate (g/s)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)
R-452B	Cal18	1.112 (larger vent, sliding window)	93.4	1457	1283
R-32	Cal09	4.476 (smaller vent, plastic film)	55.2	1241	882

The comparison of R-452B with R-32 refrigerant in Table 14 shows that room temperatures were higher for R-452B than R-32 refrigerant. Ignition of R-32 resulted in higher pressure increase, though the result is influenced by the change in vent size (vent for Cal10 thru Cal20 was 50% larger opening area than the vent used for Cal05 thru Cal09). Note that the release rate for R-452B was approximately double that of R-32 which could impact the resulting pressure and temperature.

3.3.6. Summary of Findings from Calibration Testing

1. Refrigerant release rate, release height and opening size influence pooling and mixing of the refrigerant in the test room.

2. The mixing of the refrigerant is influenced by obstructions (e.g., furniture) such that a high velocity jet does not fully mix with air and develops a local area of flammable mixture.

3. Low release velocity flows (low release rate, 356 mm opening with baffling) at 0.2 m release height resulted in pooling of the refrigerant with concentrations near the floor level higher than the upper flammability limits. In these cases, ignition occurred only after the concentration decreased below the UFL from diffusion mixing process.

4. High release velocity flows (high release rate of 100g/s, 25 mm opening) at the 2.2 m release height resulted in turbulent mixing of the jet with air. Subsequently, refrigerant concentrations were below their lower flammability limit. This test did not result in ignition. In this case, the obstruction did not influence the jet as it was below the mixing zone.

5. All but one test in the calibration series were conducted with R-32 refrigerant. Several of these tests resulted in ignitions. One test was conducted with R-452B (high release rate of 100 g/s; 25 mm opening, at 0.2 m release height) which resulted in ignition.

6. An intermediate mass release rate (55 g/s in Cal13) through the 356 mm opening with baffling at the 2.2 m release height resulted in the observation of liquid refrigerant pooling on the floor and a significant fire event. Cal17 was similar to Cal13 but at the 1.8 m release height. Liquid refrigerant was also observed pooling on the floor.

3.3.7. Test Observations, Temperature, Refrigerant Concentration and Video Documentation for Calibration Tests

Temperature: Temperature data at location B2 and D2, temperatures at A, B, C, D, and E locations at 92 and 12 inches above the floor are presented for each test. Location B2 is directly in front of the release location, and location D2 is behind the simulated obstruction and in front of the deflagration vent. The 92 in. location represents temperatures near the ceiling, and 12 in. location represents temperatures near to the floor. These data illustrate the extent of flame propagation in the test room and provide a contrast between temperatures in front of the obstruction (Location B2) to the temperatures behind the obstruction (Location D2); and also the temperatures at 92 in. height (near the ceiling) versus at 12 in height (near the floor) (Refer to Figure 34).

Refrigerant Concentration: The refrigerant concentration at the four locations (1 in., 1 ft., 2 ft., and 3 ft.) above the floor (Refer to Figure 34).

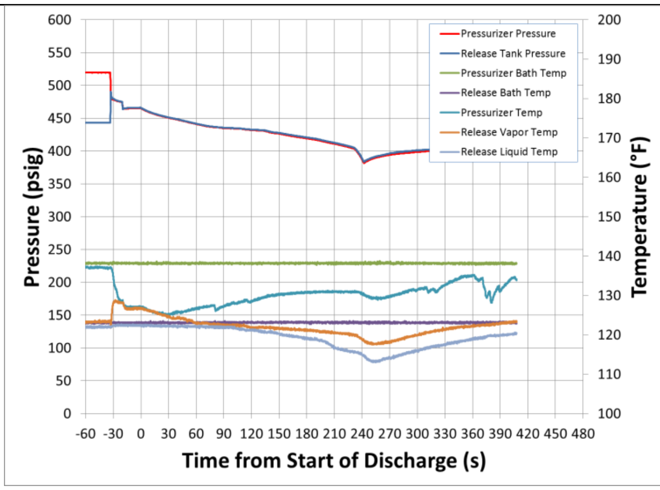
Video Documentation: In addition, stills from video cameras provide documentation of the refrigerant release and ignition events.

Spreadsheet-style summaries of all of the following tests are included in Appendix B Task 1 Test Data Summary.

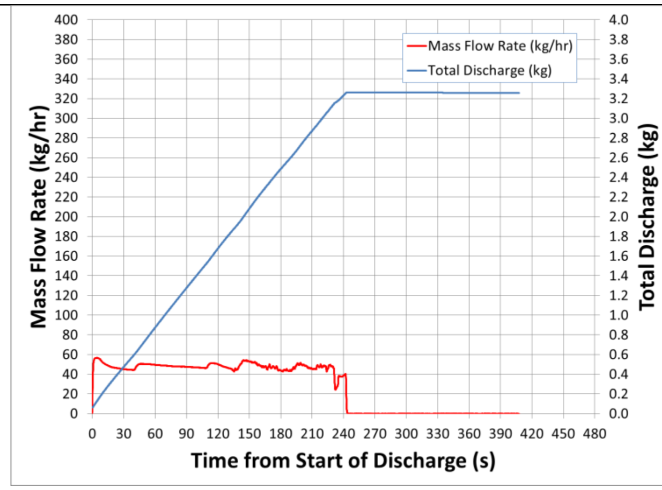
Test Cal05: The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Release Height (m)	Release opening Size (mm Diameter)	Ignition Result
R-32	13.5	2.2	25	Ignition

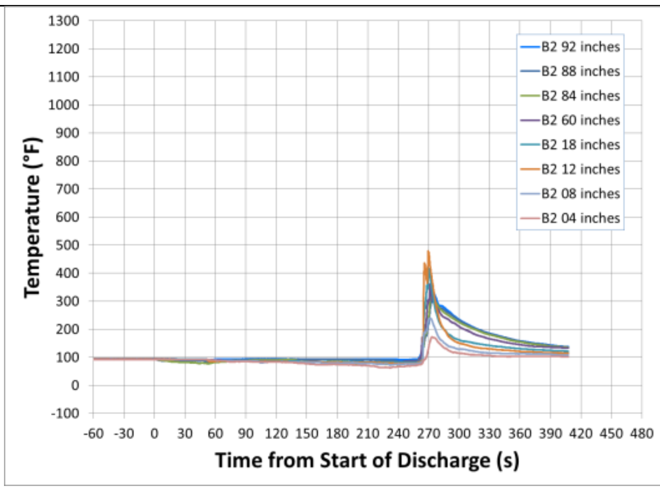
There was ignition immediately after electric arcs were initiated. The fire event lasted approximately 30s. Selected data from the test are shown in Figure 41.



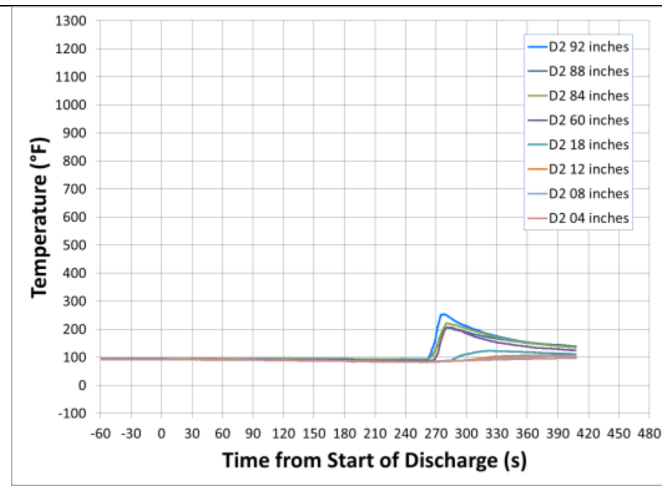
Pressure and Temperature in Pressurizer and Release Tanks



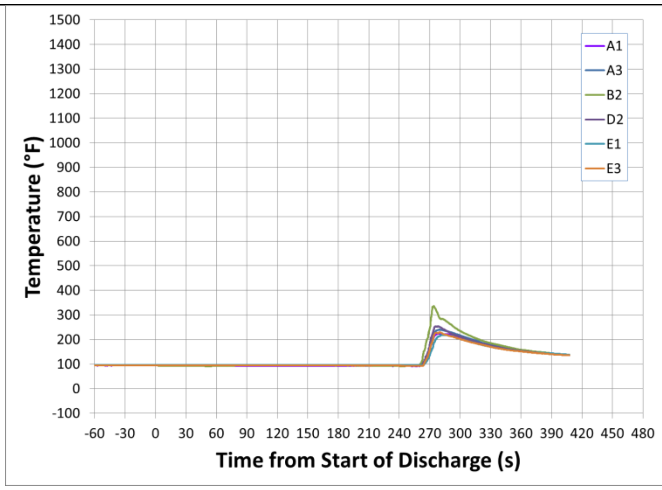
Refrigerant Release Rate



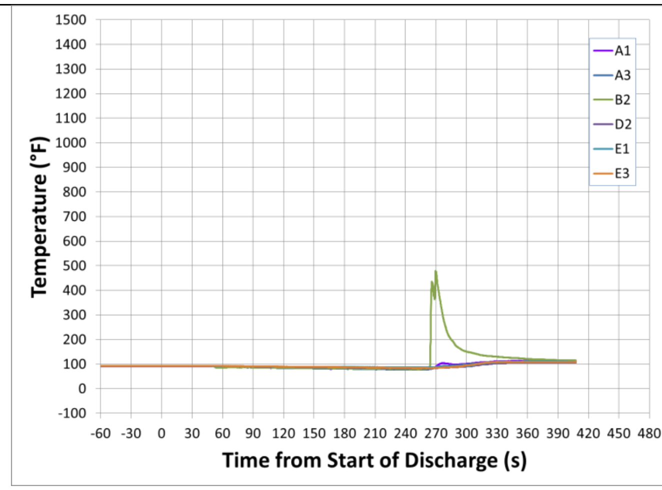
Temperature at Location B2



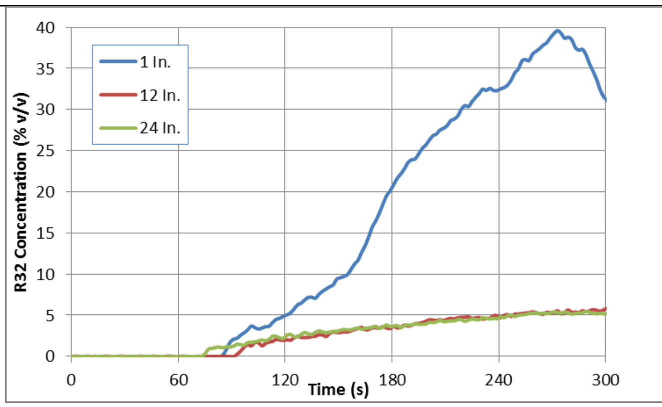
Temperature at Location D2



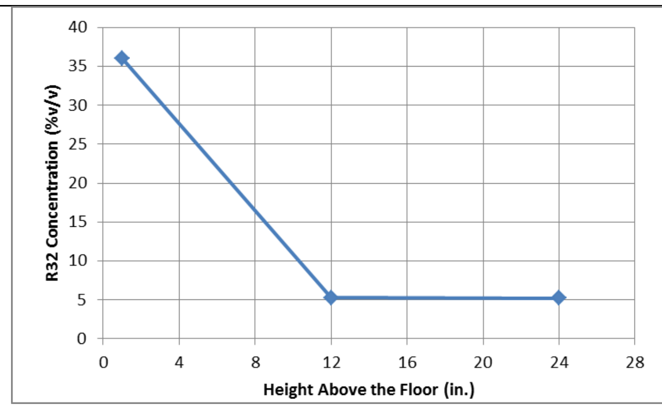
Temperature at 92 in. height above the floor



Temperatures at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

Electric arcs after release: 4:02

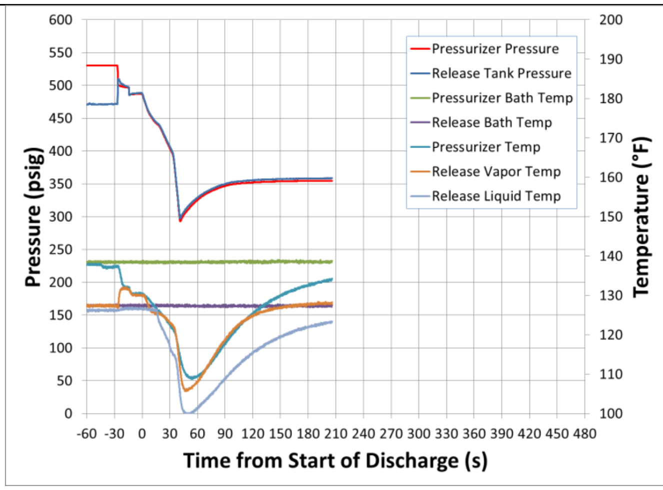
15s after Electric arcs

Figure 41 – Data from Cal05

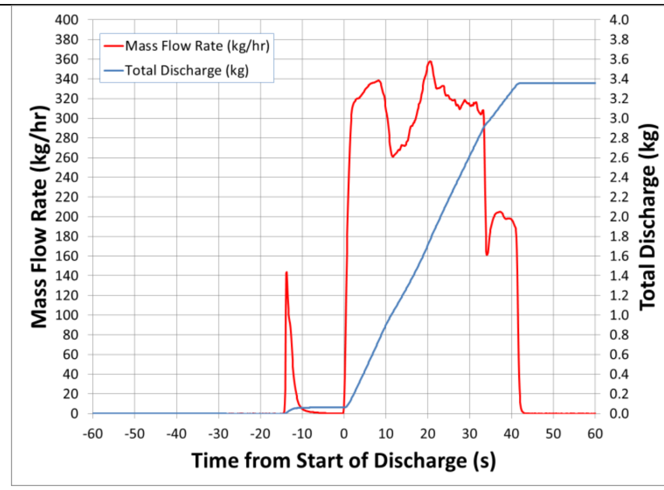
Test Cal06: The test parameters were as follows:

Refrigerant	Release rate (g/s)	Release Height (m)	Release opening Size (mm Diameter)	Ignition Result
R-32	100	2.2	25	No Ignition

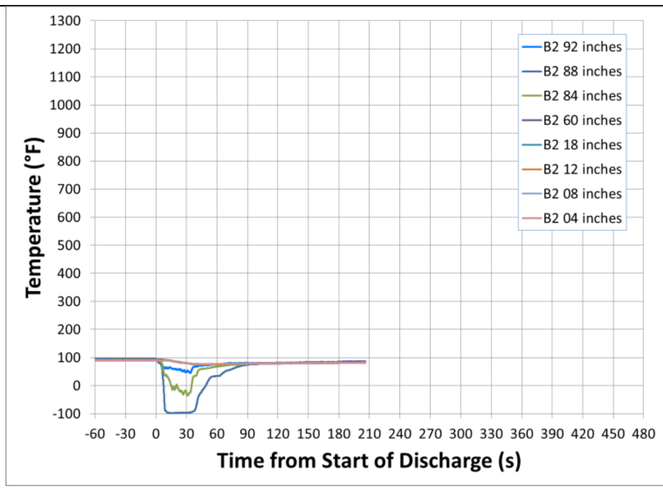
There was no ignition of the released refrigerant. Selected data from the test are shown in Figure 42.



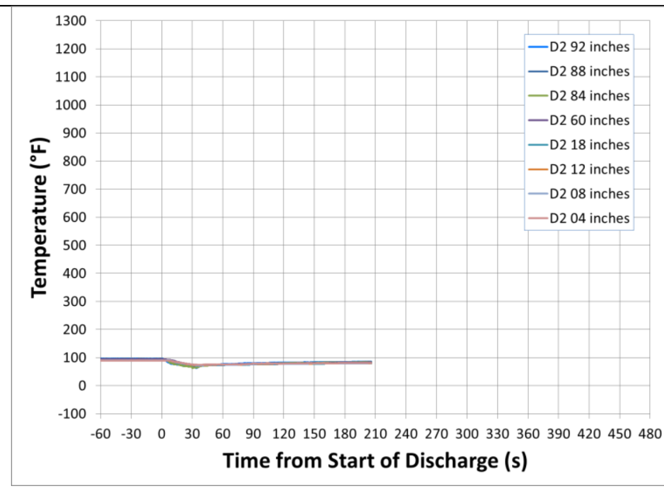
Pressure and Temperature in Release and Pressurizer Tanks



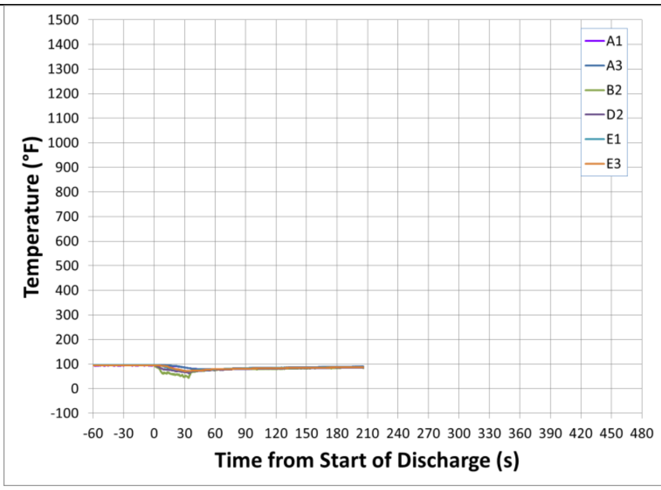
Refrigerant Release Rate



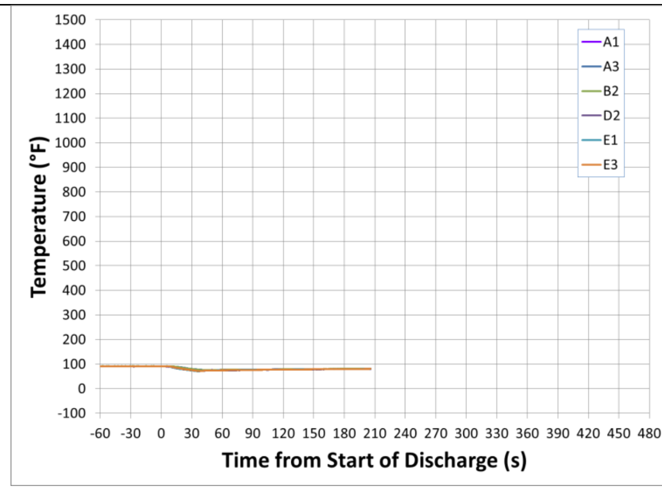
Temperature at Location B2



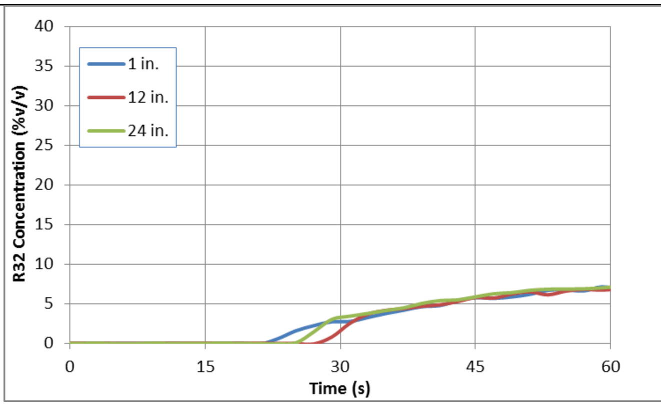
Temperature at Location D2



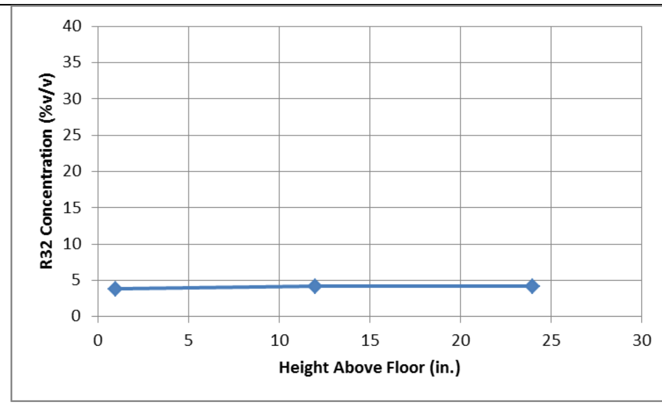
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

Conditions at the end of refrigerant release

60s after end of release (no ignition)

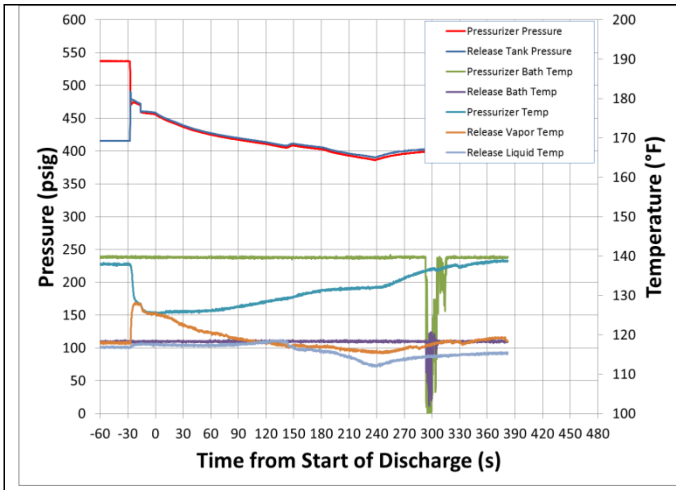
Figure 42 – Data from Cal06

Test Cal07: The test parameters were as follows:

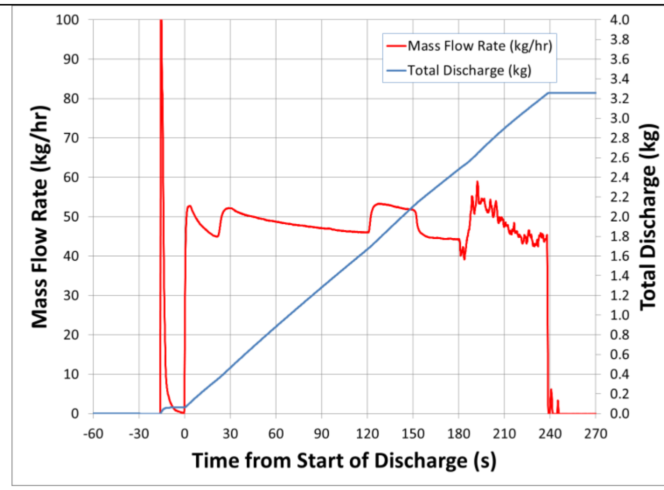
Refrigerant	Release rate (g/s)	Release Height (m)	Release opening Size (mm Diameter)	Ignition Result
R-32	13.5	0.2	25	Ignition

The refrigerant in the presence of the electric arcs created dark smoke particles after release at the 1-inch level electric arc. Flame propagation moving away from the electric arc was observed 23 s after the electric arcs were energized. Flaming continued for approximately 1 minute. Ignition and subsequent flames started between the 1 ft. and 2 ft. level indicating a layer of gas above the UFL below this layer. The test facility door (30ft x 30 ft. room) opened due to pressure rise and not being latched correctly. The door opening coincided with the ISO room deflagration vent melting away. The original (smaller) deflagration vent was still configured in test Cal07 and was not reconstructed until before Cal10.

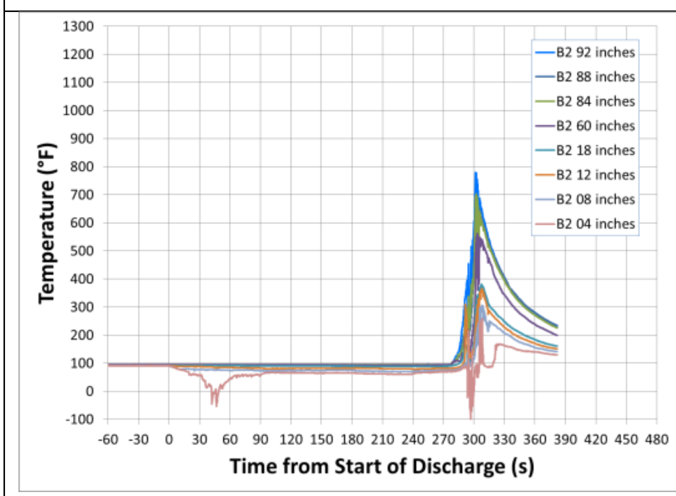
Selected data from the test are presented in Figure 43.



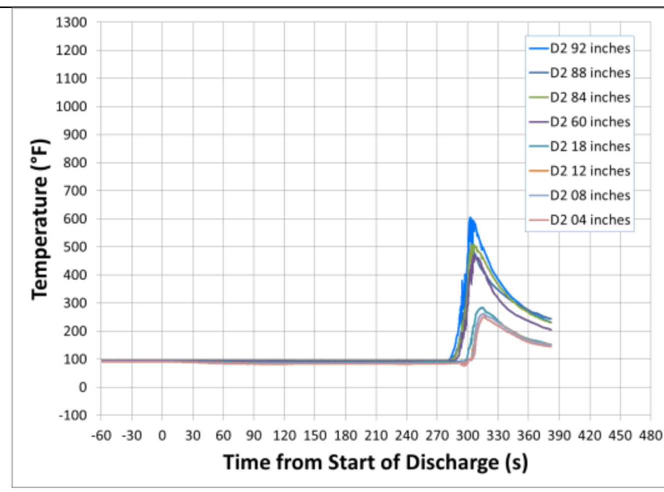
Pressure and Temperature in Release and Pressurizer Tanks



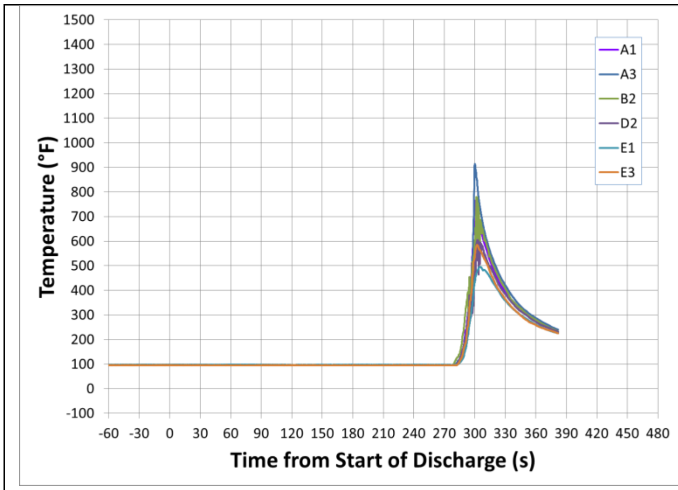
Refrigerant Release Rate



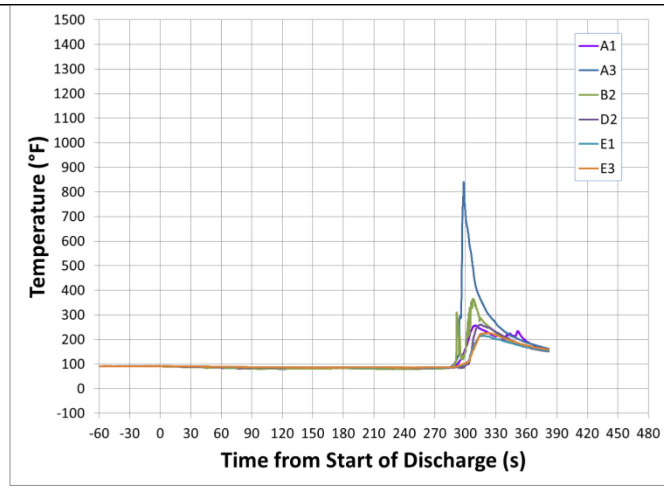
Temperature at Location B2



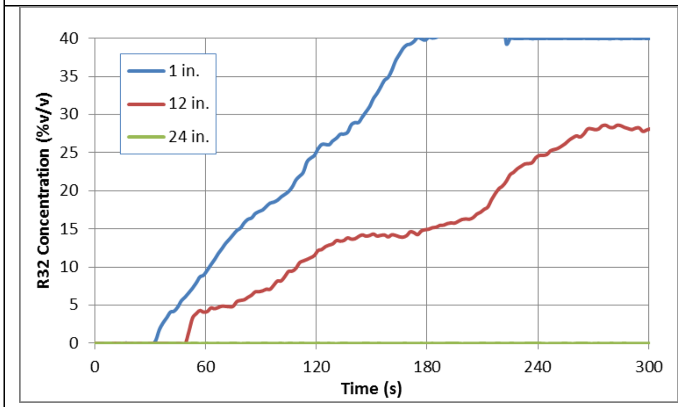
Temperature at Location D2



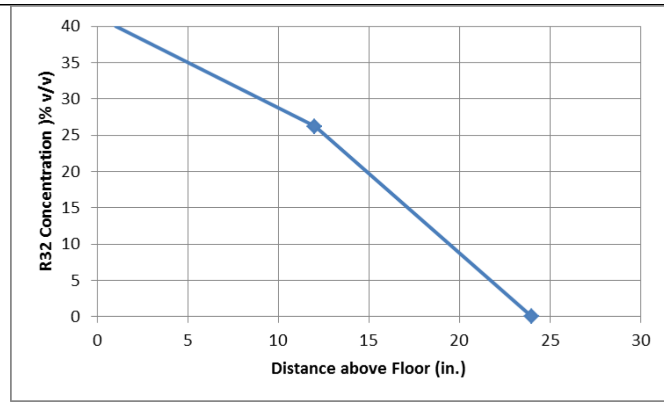
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentrarion when Electric arcs are Energized

End of release; Electric arc initiated

42s after Electric arc initaition

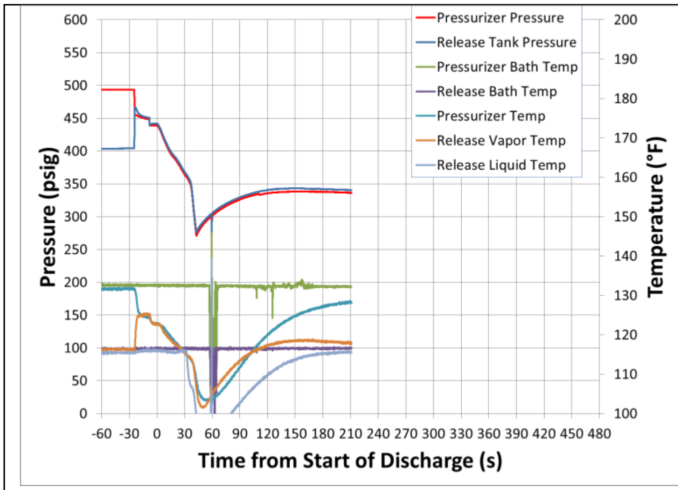
Figure 43 – Data from Cal07

Test Cal08: The test parameters were as follows:

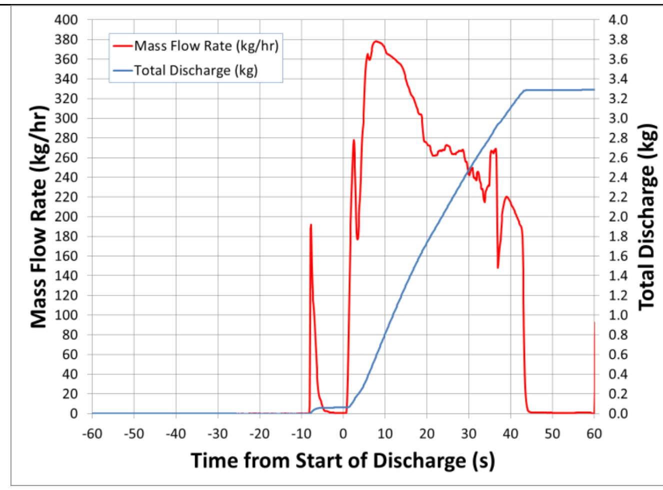
Refrigerant	Release rate (g/s)	Release Height (m)	Release opening Size (mm Diameter)	Ignition Result
R-32	100	0.2	25	Ignition

The refrigerant mixture ignited with the application of electric arcs and the mixture burned for approximately 25 s. There was significant electric arcing with sparks visible from the aluminum foil wraps. The thermocouple at the release opening became loose and did not record the release temperature. This test was repeated and is shown as Cal09 test record.

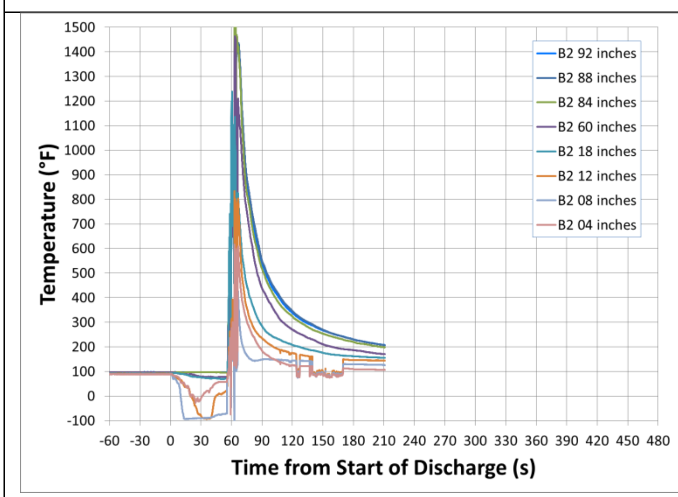
Selected data from the test are presented in Figure 44. The spike in the refrigerant concentration data was an interference signal from the electric arc.



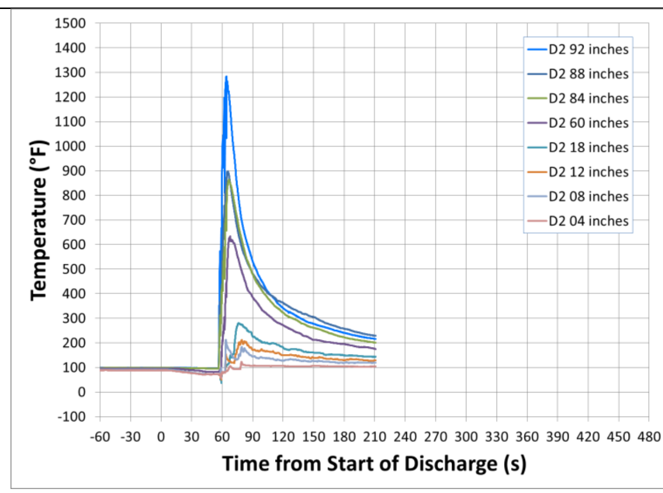
Pressure and Temperature in Release and Pressurize Tanks



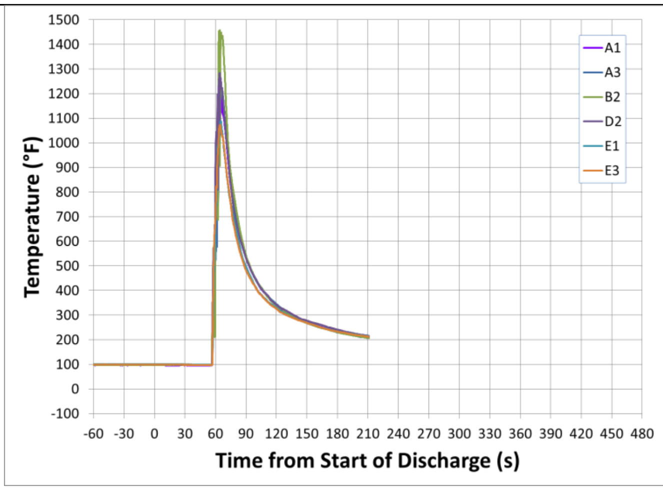
Refrigerant Release Rate



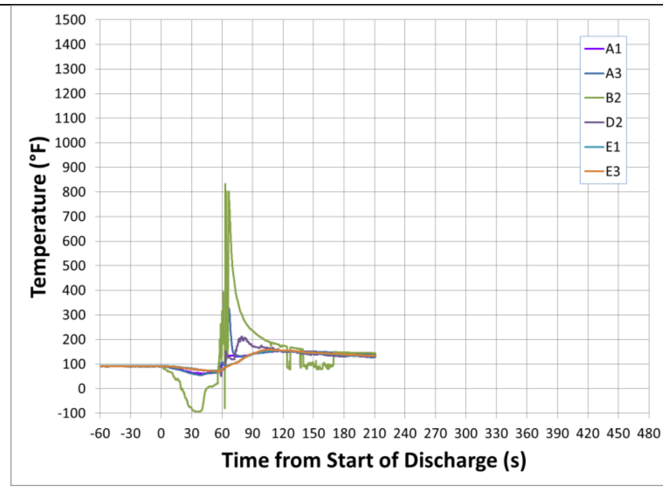
Temperature at Location B2



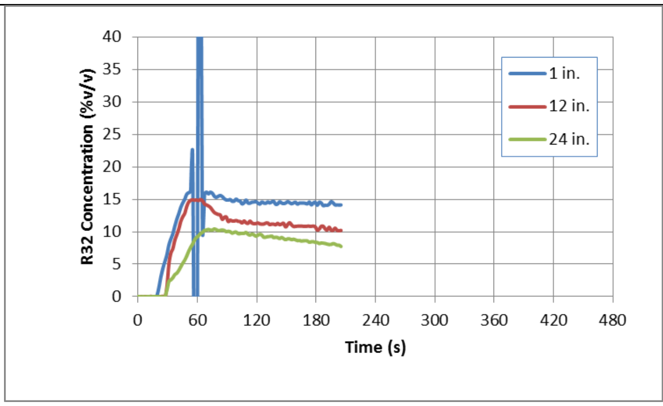
Temperature at Location D2



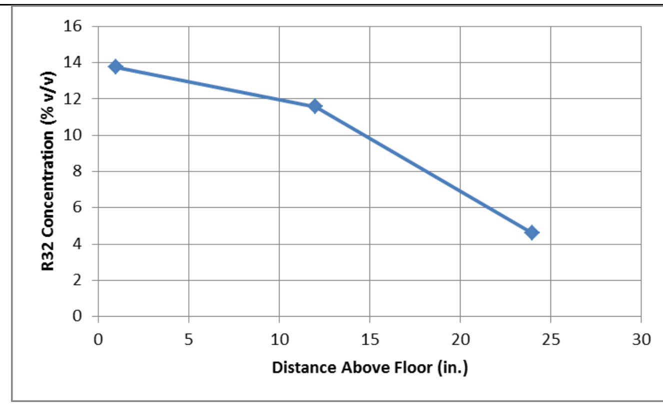
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor

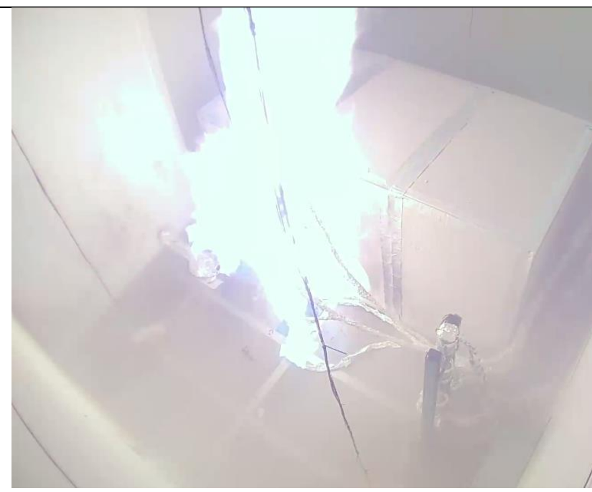


Refrigerant Concentration



Refrigerant Concentrarion when Electric arcs are Energized

Refrigerant mixture at end of release



Electric arcs energized:
Ignition of Refrigerant

Figure 44 – Data from Cal08

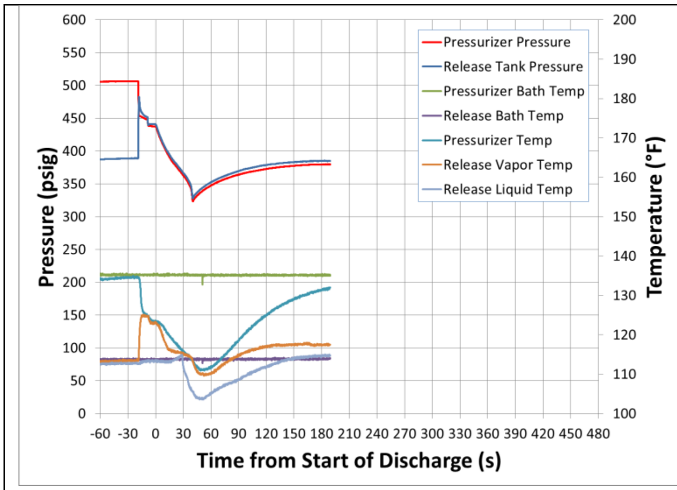
Test Cal09: The test parameters were as follows:

Refrigerant	Release rate (g/s)	Release Height (m)	Release opening Size (mm Diameter)	Ignition Result
R-32	100	0.2	25	Ignition

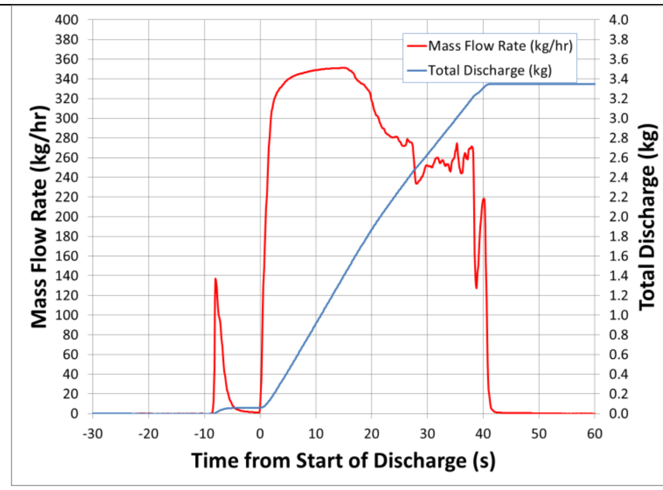
Deflagration in the test room was observed immediately after initiating the electric arcs. The event was energetic enough to displace the test room walls with the pressure. The event lasted approximately 10s.

It was observed that the plastic sheet covering the deflagration vent did not vent fast enough and enabled pressure build up in the test room. The deflagration vent was redesigned with a sliding metal door to prevent excessive pressure build-up in the test fixture.

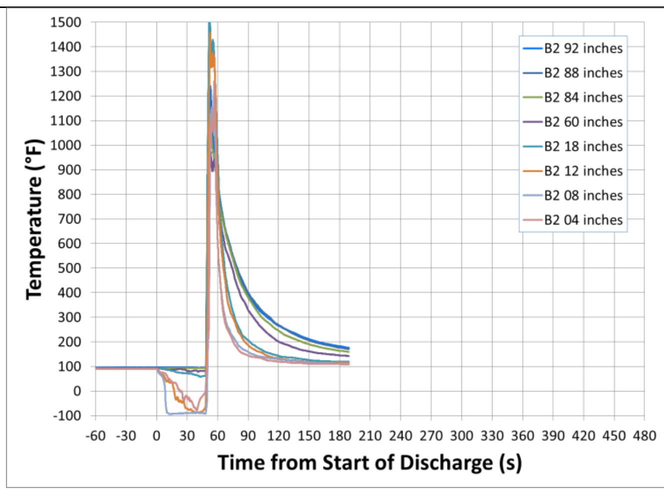
Selected data for the test are presented in Figure 45.



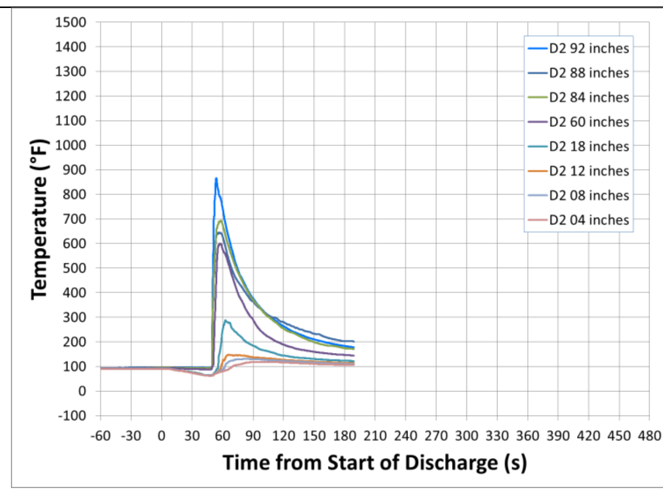
Pressure and Temperature in Release and Pressurizer Tanks



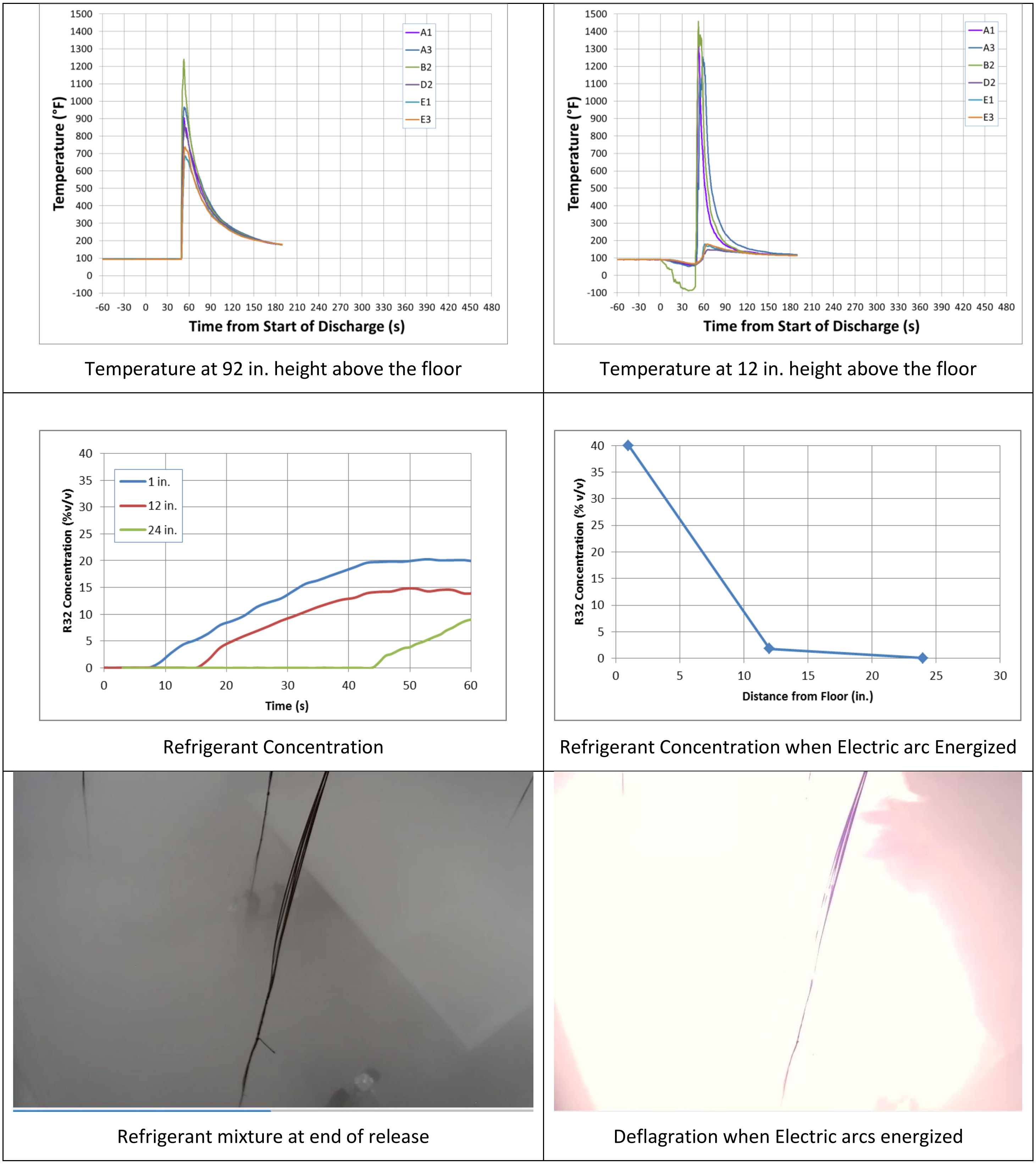
Refrigerant Release Rate



Temperature at Location B2



Temperature at Location D2



Temperature at 92 in. height above the floor

Temperature at 12 in. height above the floor

Refrigerant Concentration

Refrigerant Concentration when Electric arc Energized

Refrigerant mixture at end of release

Deflagration when Electric arcs energized

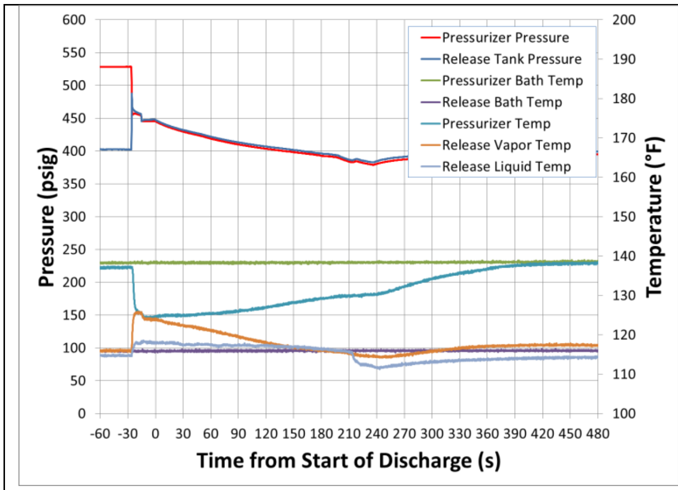
Figure 45 – Data from Cal09

Test Cal10: The test parameters were as follows:

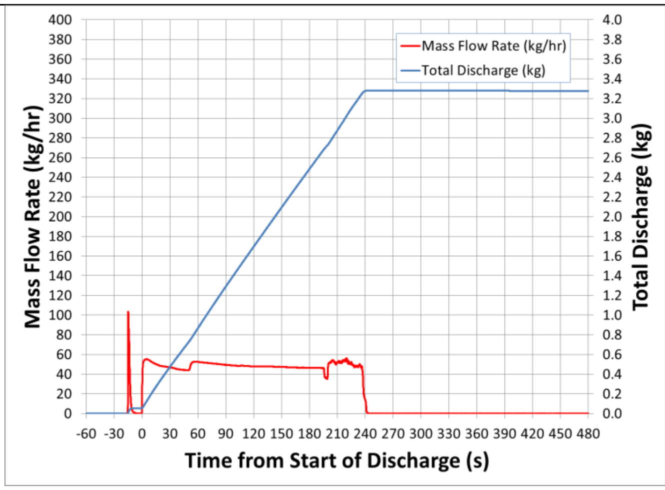
Refrigerant	Release rate (g/s)	Release Height (m)	Release opening Size (mm Diameter)	Ignition Result
R-32	13.5	0.2	356	Ignition

There was no ignition during the three minutes following release due to floor level refrigerant concentration higher than the UFL. Since this pooling represented an ignition potential, a second attempt was made after refrigerant concentration was observed to be between the LFL and UFL. The Electric arcs were de-energized and the sample pump turned on. When concentration at the 1-inch level was recorded at 34% and dropping the electric arcs were re-energized approximately six minutes after end of refrigerant release. Ignition occurred at about the 6 inch level, eventually extending down to the level of the floor, and flames were visible for approximately 30s after ignition.

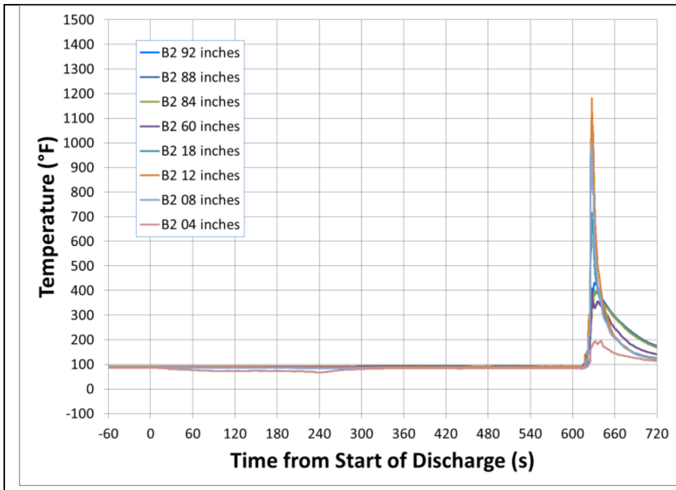
Selected data for the test are presented in Figure 46.



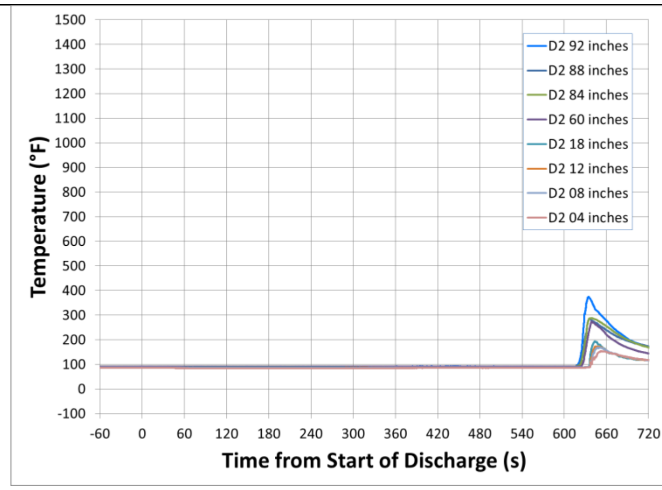
Pressure and Temperature of Release and Pressure Tanks



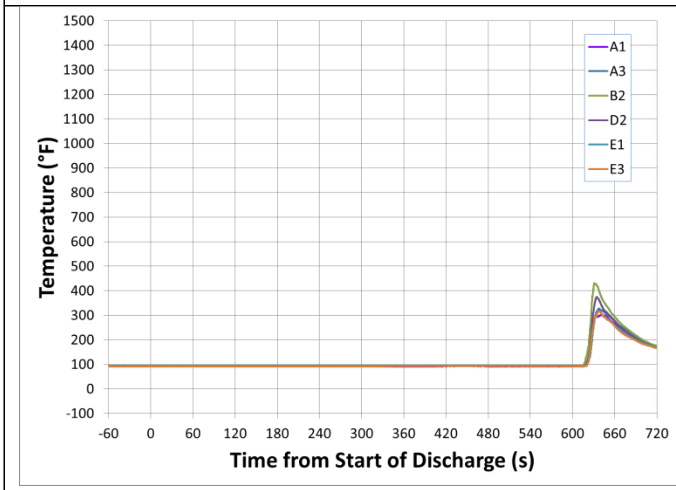
Release Rate



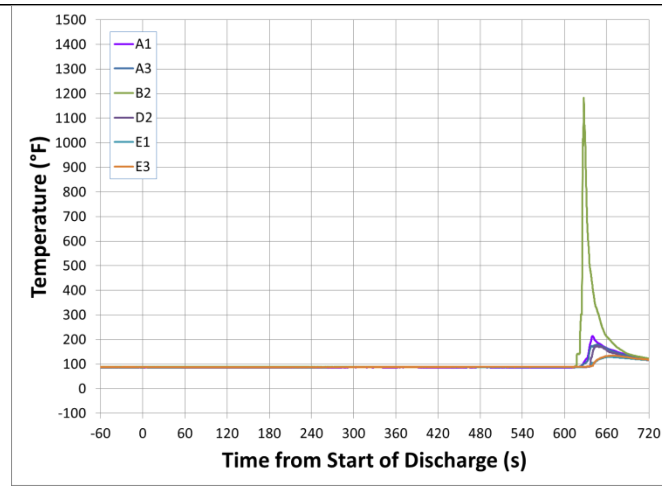
Temperature at Location B2



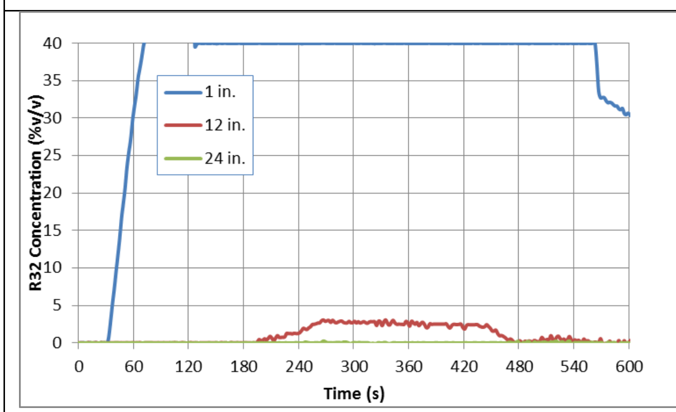
Temperature at Location D2



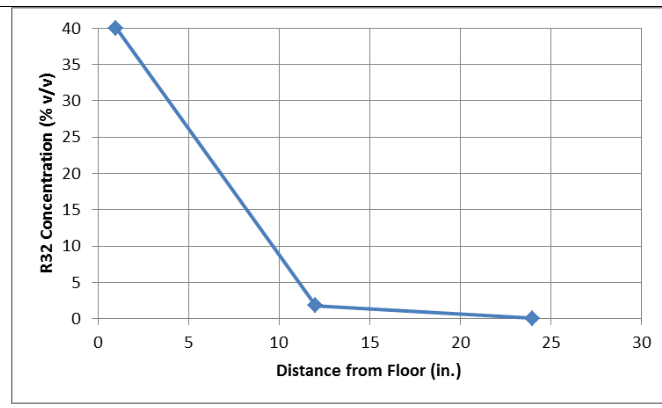
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

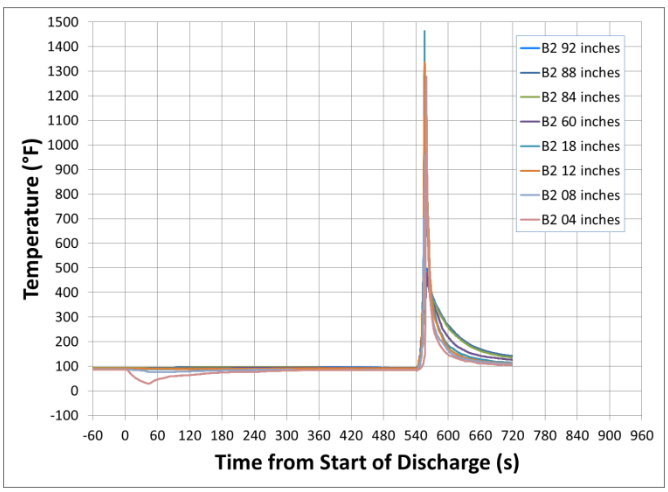
Figure 46 – Data from Cal10

Test Cal11: The test parameters were as follows:

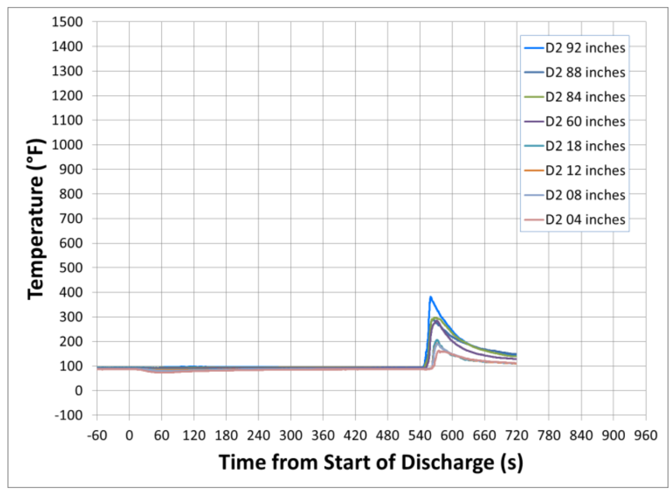
Refrigerant	Release rate (g/s)	Release Height (m)	Release opening Size (mm Diameter)	Ignition Result
R-32	100	0.2	356	Ignition

There was no ignition during the three minutes following release and the electric arcs were de-energized and the sample pump turned on. When concentration at the 1-inch level was recorded at 34% and falling, the electric arcs were re-energized at approximately 8 minutes after the end of refrigerant release. Subsequently, ignition occurred at about the 6 inch level, eventually extending down to the level of the floor, and flaming continued for approximately 40s.

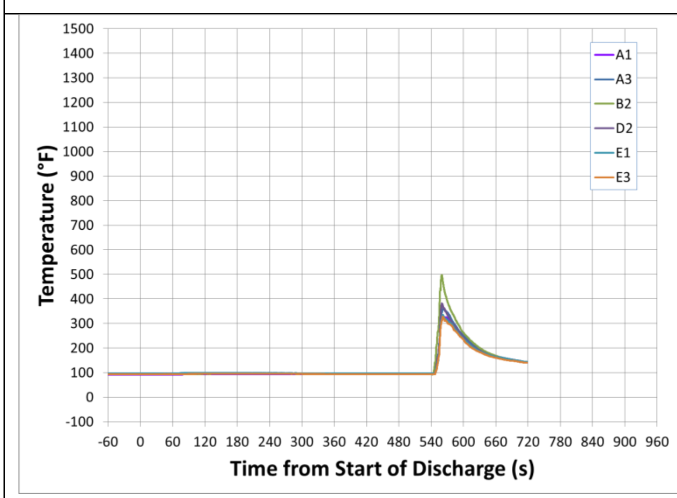
Selected data for the test are presented in Figure 47.



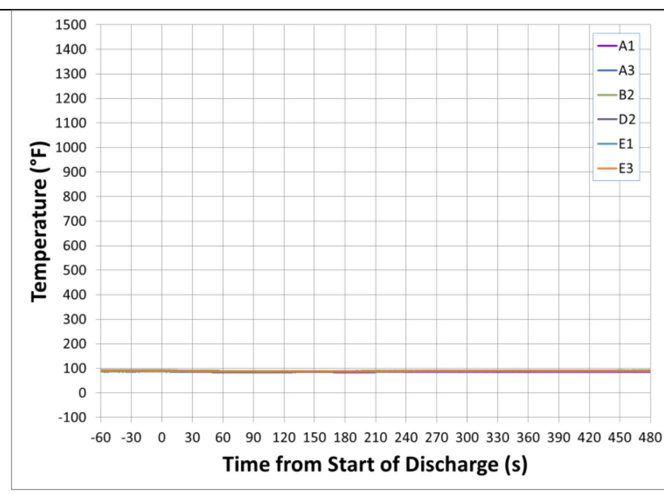
Temperature at Location B2



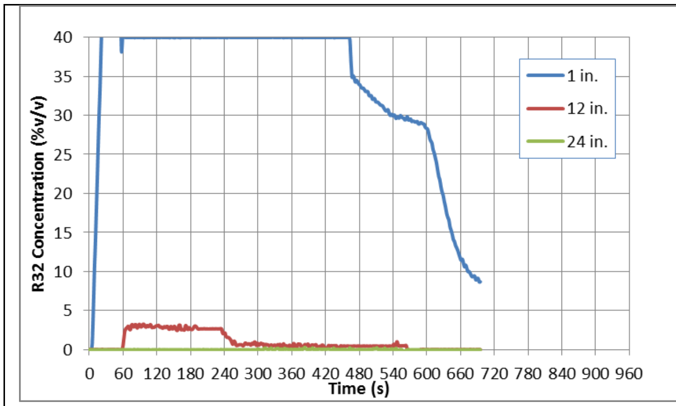
Temperature at Location D2



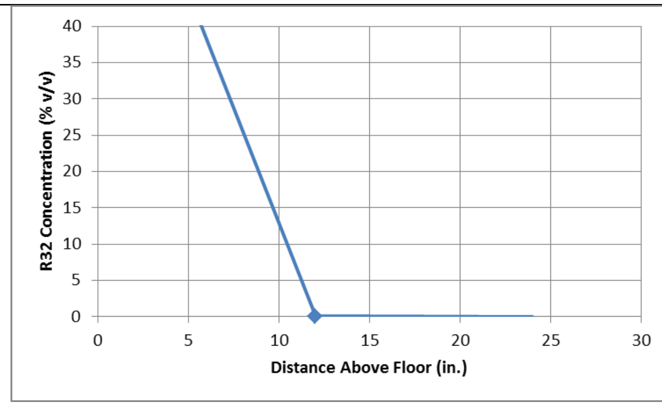
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration When Electric arcs are Energized at 60s (first attempt)

After First Attempt with Electric arcs

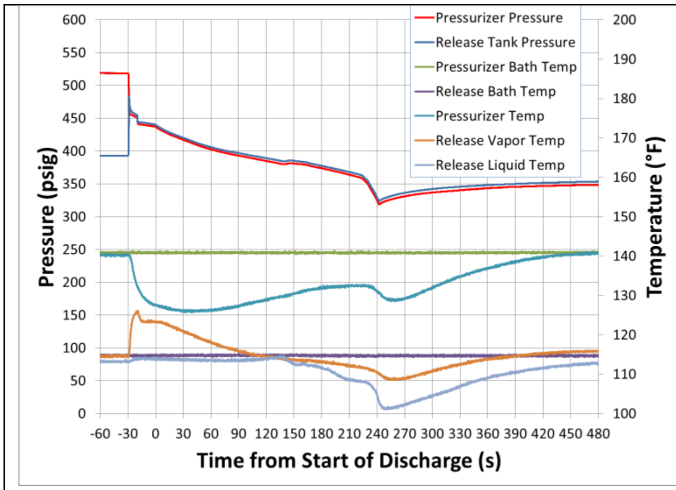
Ignition of the Refrigerant after Second Attempt

Figure 47 – Data from Cal011

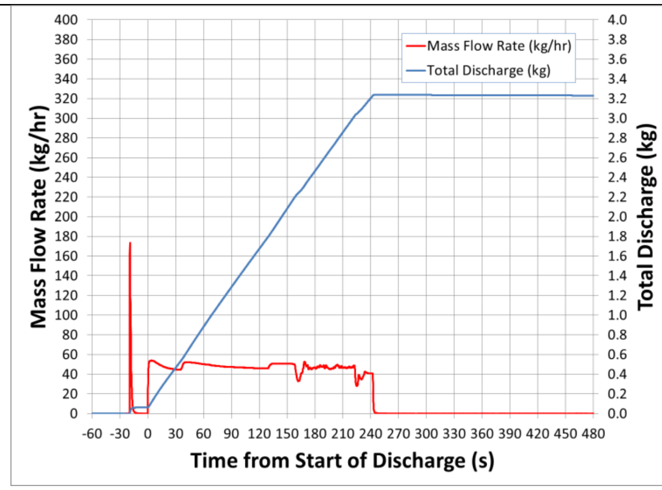
Test Cal12: The test parameters for the test were as follows:

Refrigerant	Release rate (g/s)	Release Height (m)	Release opening Size (mm Diameter)	Ignition Result
R-32	13.5	2.2	356	No Ignition

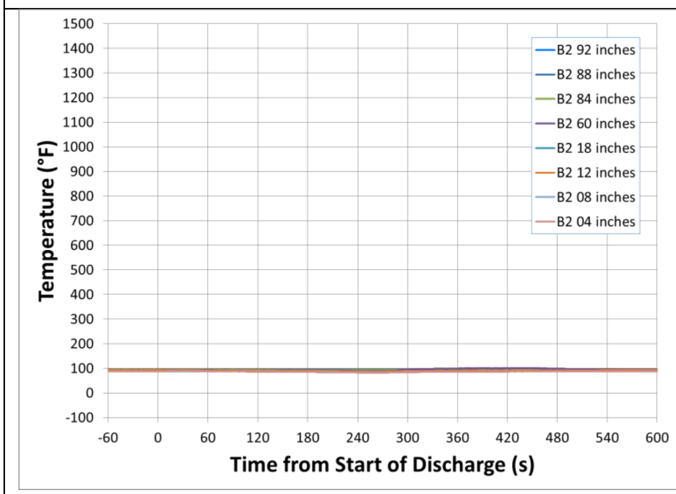
There was no ignition of the released refrigerant in the test room. Selected data for the test are presented in Figure 48.



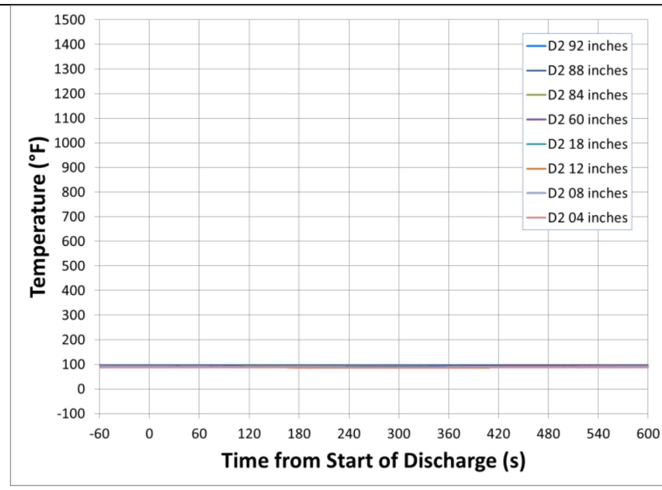
Pressure and Temperature of Release and Pressurizer Tanks



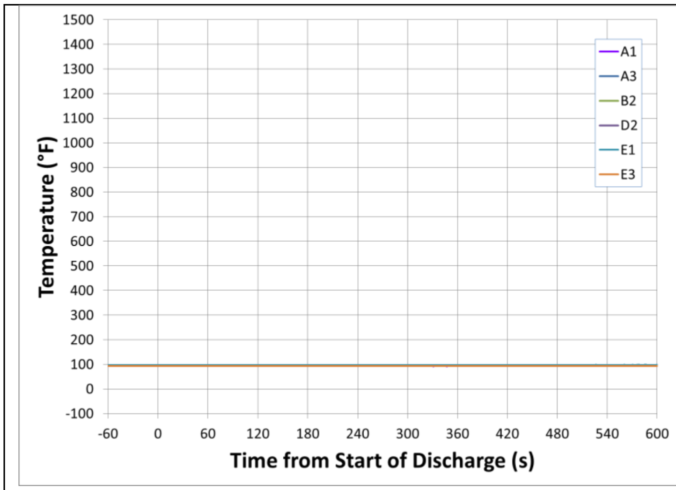
Refrigerant Release Rate



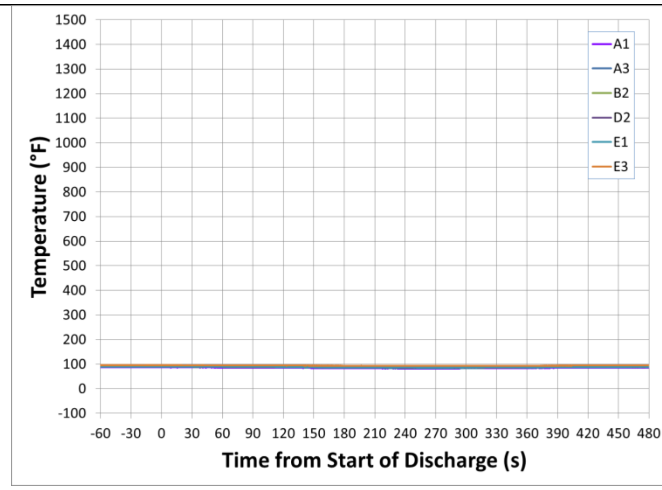
Temperature at Location B2



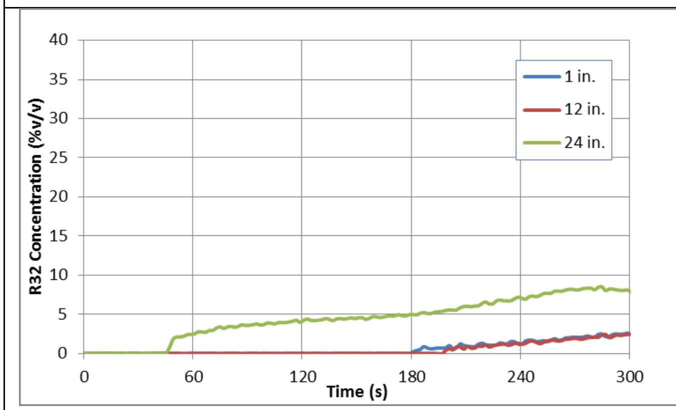
Temperature at Location D2



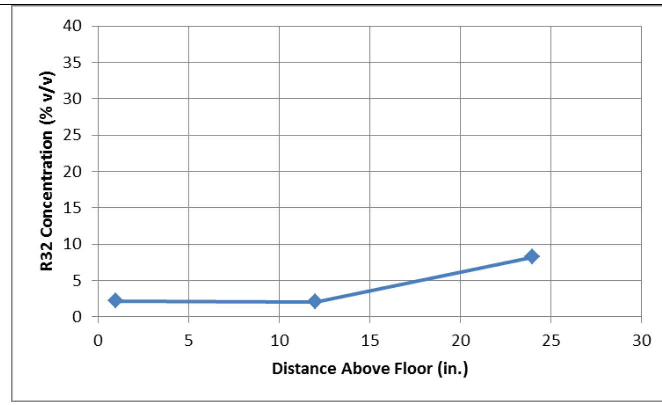
Temperature at 92 in. height above the floor



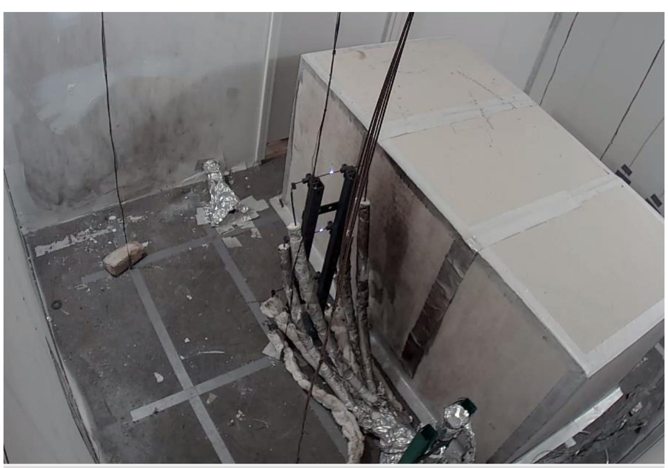
Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized



End of Refrigerant Release (Electric arcs Energized)

3 Minutes after End of Refrigerant Release

Figure 48 – Data from Cal012

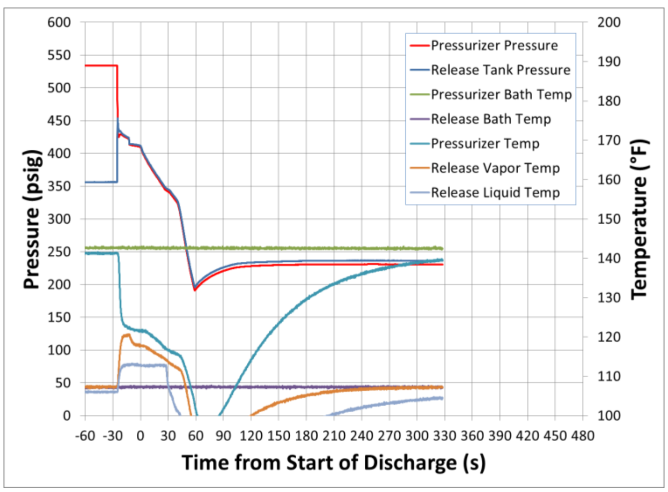
Test Cal13: The test parameters for the test were as follows:

Refrigerant	Release rate (g/s)	Release Height (m)	Release opening Size (mm Diameter)	Ignition Result
R-32	100 [1]	2.2	356	Ignition

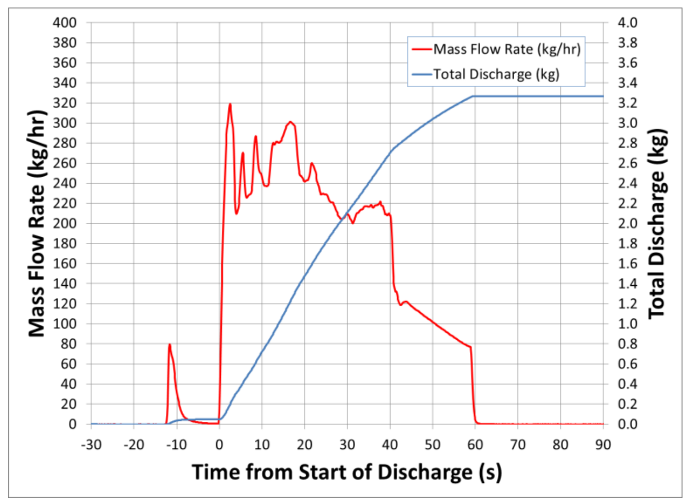
[1] - Actual average release rate was 55.2 g/s.

There was ignition immediately after electric arcs were energized at the end of refrigerant release. The flaming continued for approximately 12 s.

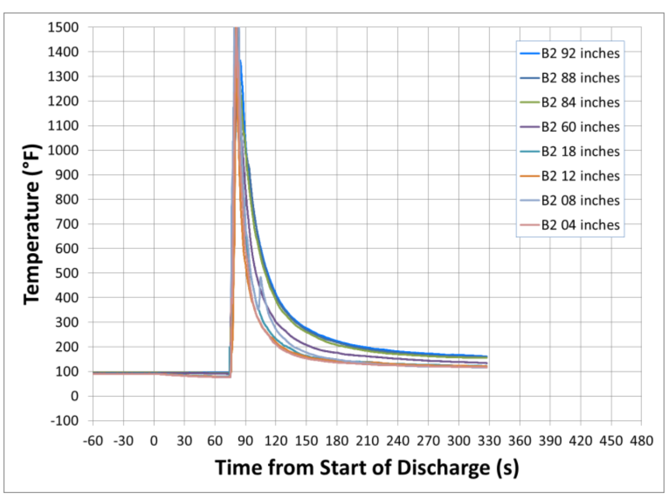
Selected data for test are presented in Figure 49.



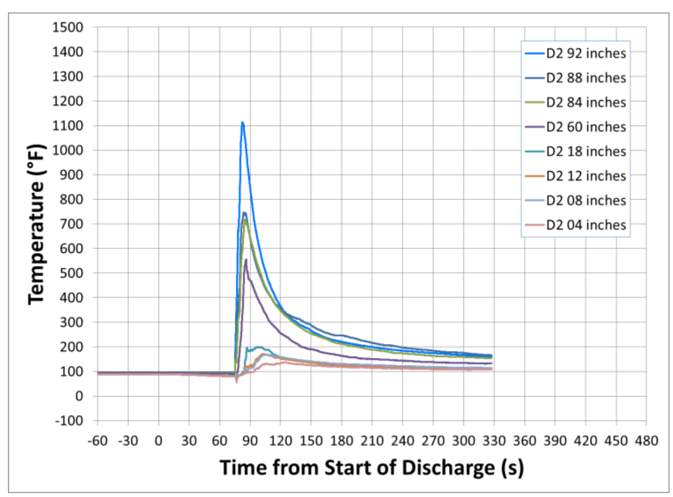
Pressure and Temperature for Release and Pressurizer Tanks



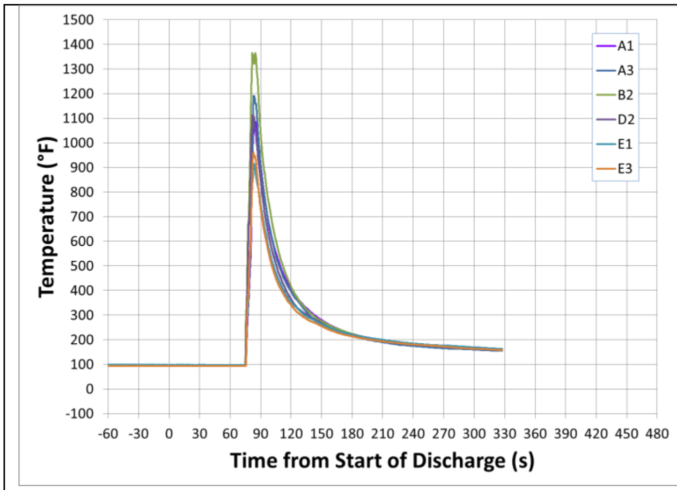
Refrigerant Release Rate



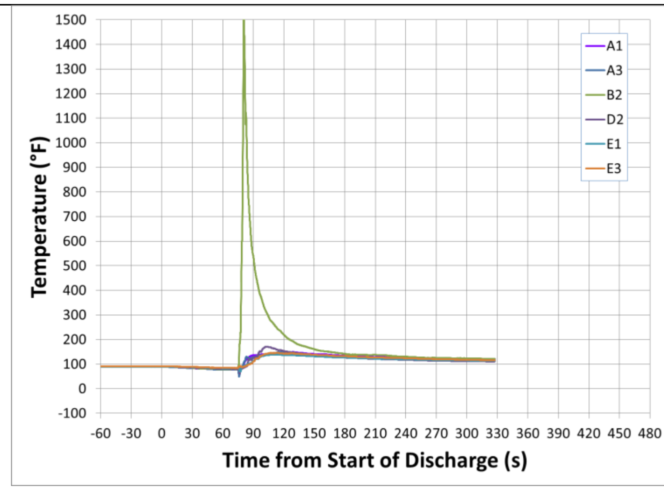
Temperature at Location B2



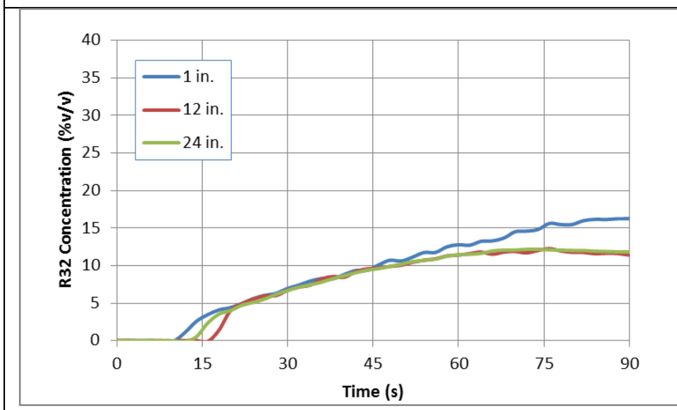
Temperature at Location D2



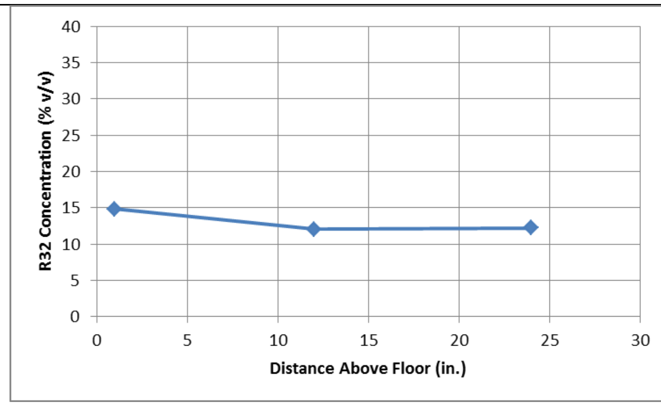
Temperature at 92 in. height above the floor



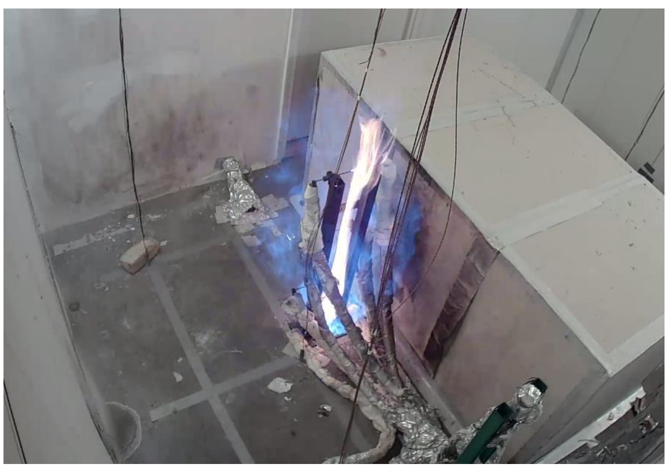
Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized



End of Refrigerant Release when Electric arcs are Energized

7 s after Energizing Electric arcs

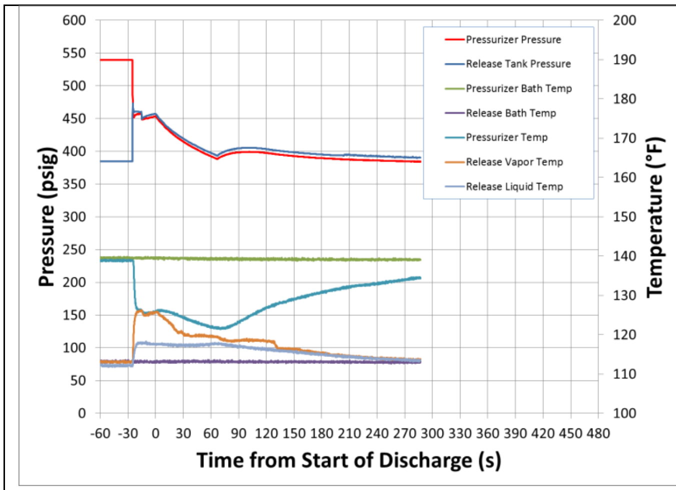
Figure 49 – Data from Cal13

[Note Cal14 and Cal15 test codes were used for the room leakage test and are discussed in 3.2.5 Characterization of Test Room Leakage.]

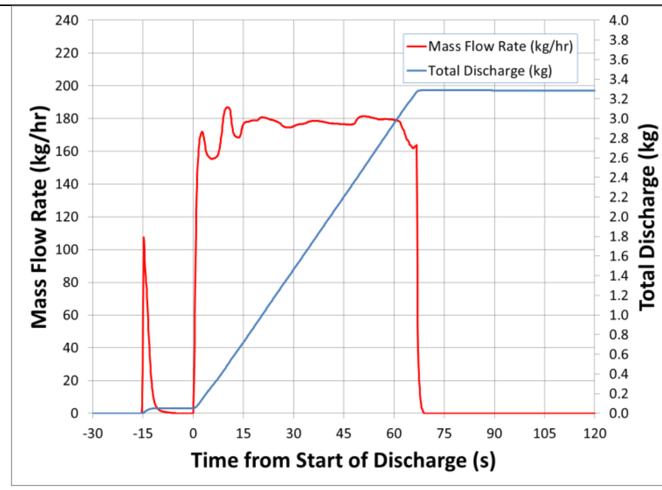
Test Cal16: The parameters for the test were as follows:

Refrigerant	Release rate (g/s)	Release Height (m)	Release opening Size (mm Diameter)	Ignition Result
R-32	50	1.8	25	Ignition

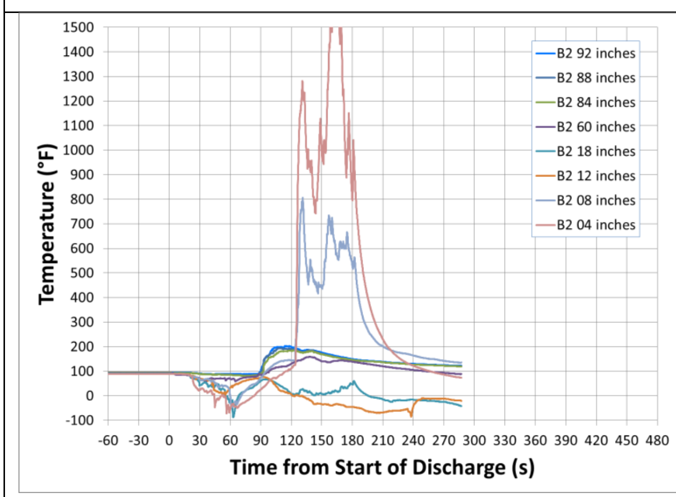
The refrigerant ignited when the electric arcs were energized at the end of refrigerant release, and flaming continued for approximately 50s. Selected data for the test are presented in Figure 50.



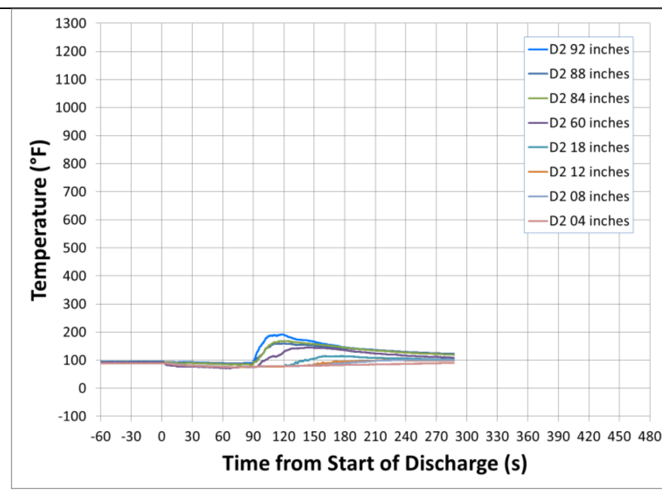
Pressure and Temperature in Release and Pressurizer Tanks



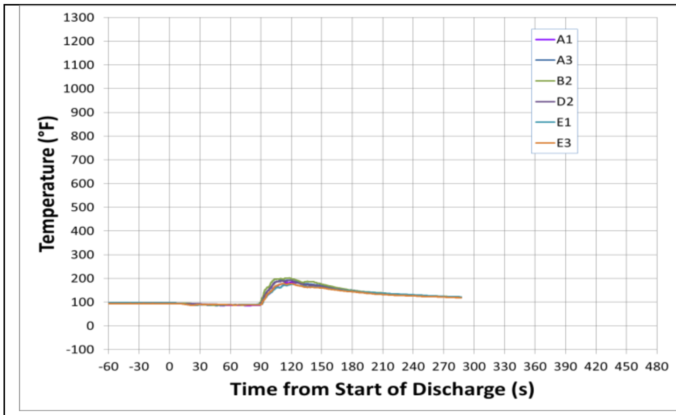
Refrigerant Release Rate



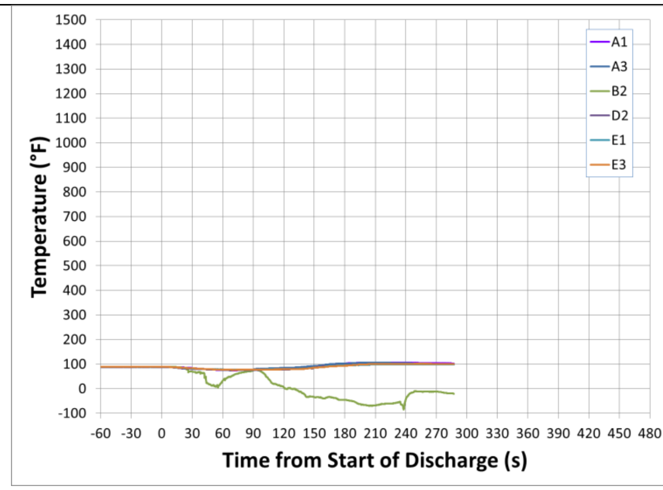
Temperature at Location B2

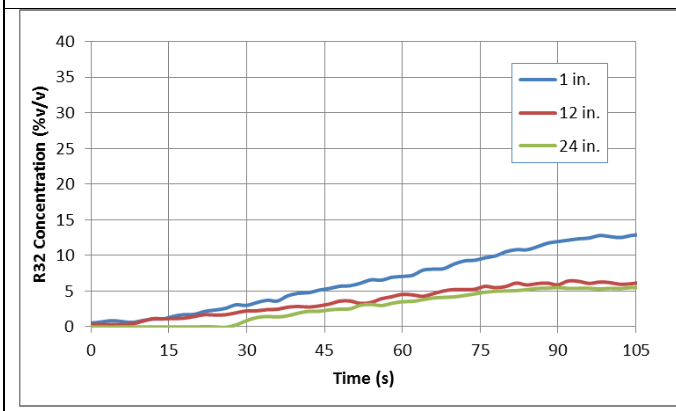


Temperature at Location D2

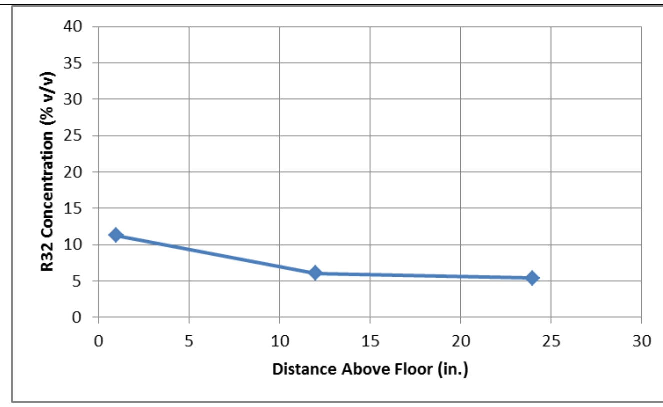


Temperature at 92 in. height above the floor





Refrigerant Concentration



Refrigerant Concentration when Electric Sarks were Energized

End of Refrigerant Release and Electric arcs Energized

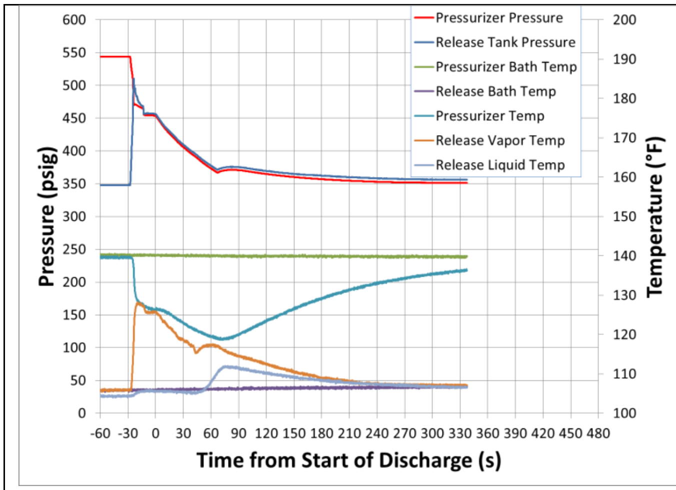
9 s after Electrical arcs were Energized

Figure 50 – Data from Cal16

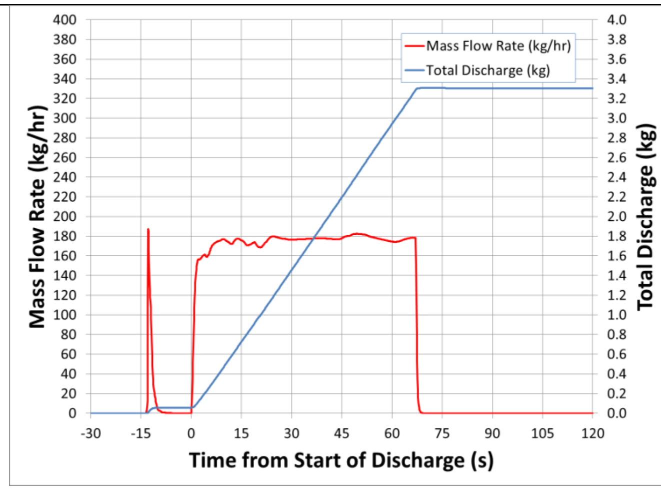
Test Cal17: The parameters for the test were as follows:

Refrigerant	Release rate (g/s)	Release Height (m)	Release opening Size (mm Diameter)	Ignition Result
R-32	50	1.8	356	Ignition

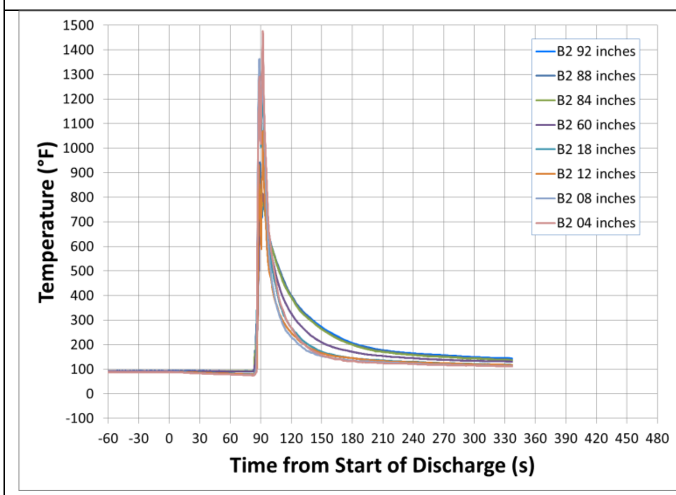
The refrigerant ignited in the test room when the electric arcs were energized at the end of refrigerant release. Flaming continued for another 50 s, with the flaming moving toward the release source. The refrigerant sensors (deconvoluted data) did not show concentrations above the LFL. The videos show that flames did not come near the refrigerant sensors indicating that the volume of gas mixture above the LFL was concentrated near the centerline of the test room.



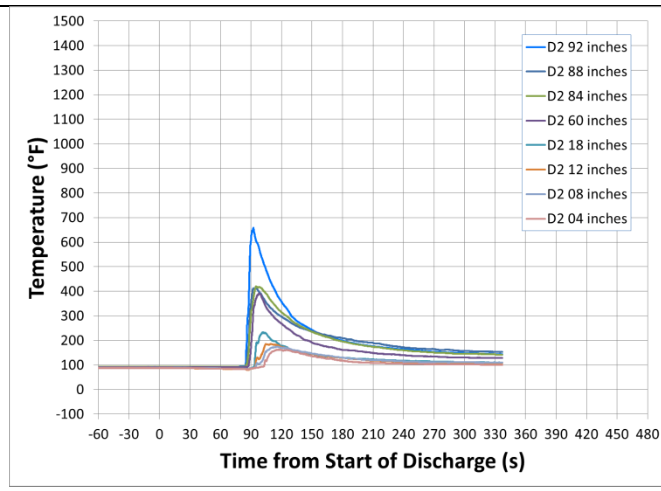
Pressure and Temperature of Release and Pressurizer Tanks



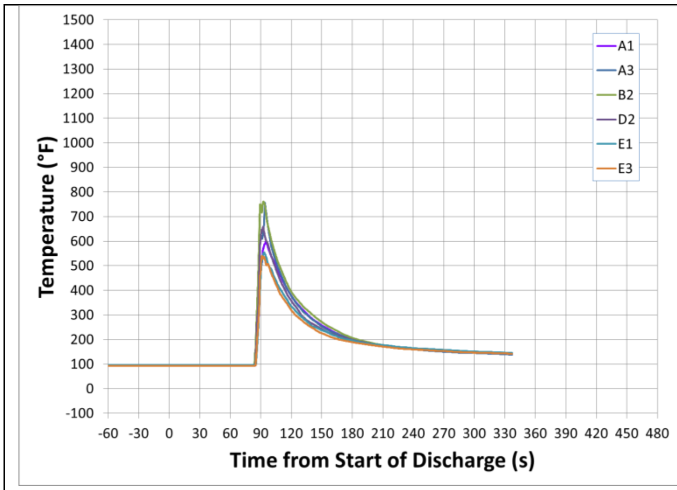
Refrigerant Release Rate



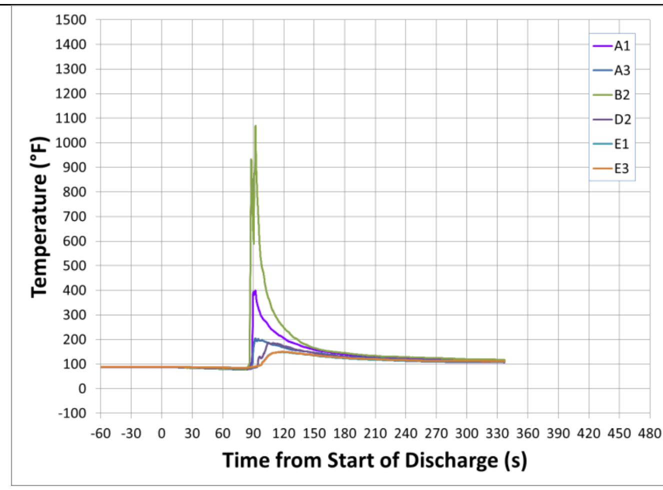
Temperature at Location B2



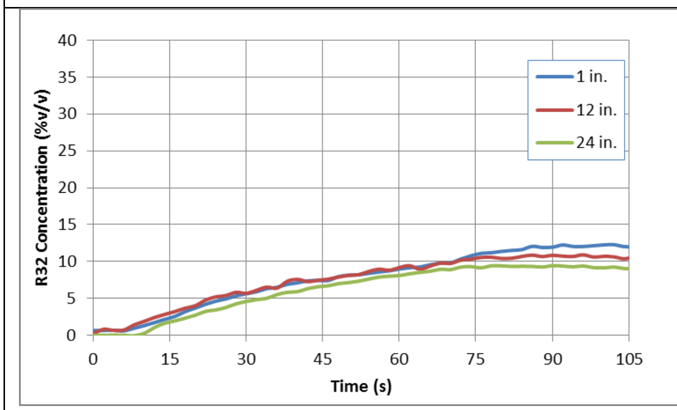
Temperature at Location D2



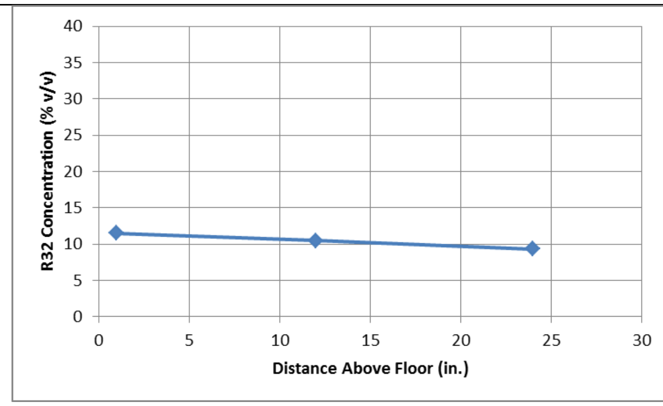
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

Ignition of the Refrigerant upon Energizing the Electric arcs

7s after Engerizing Electric arcs

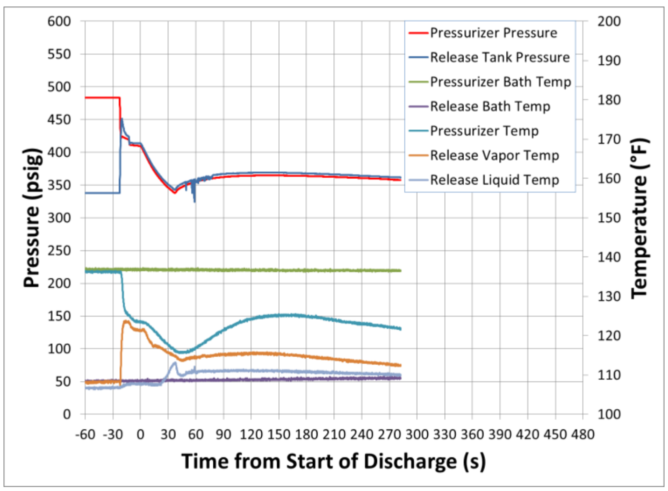
Figure 51 – Data from Cal17

Test Cal18: This test was conducted with R-452B refrigerant. The test parameters selected were based upon R-32 test results, where consistent ignition and flaming were observed.

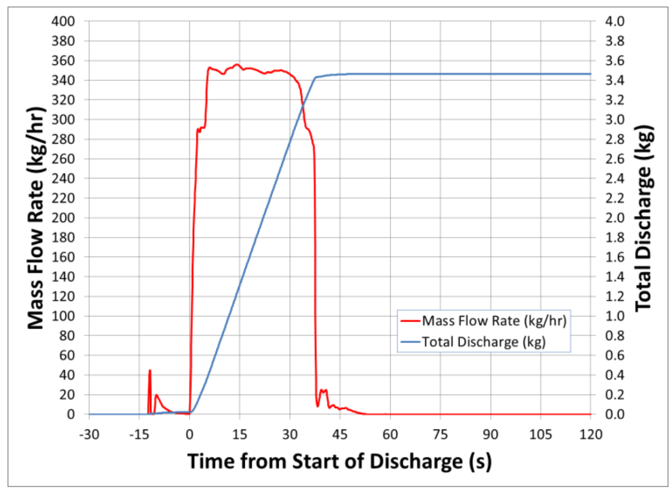
The parameters for the test were as follows:

Refrigerant	Release rate (g/s)	Release Height (m)	Release opening Size (mm Diameter)	Ignition Result
R-452B	100	0.2	25	Ignition

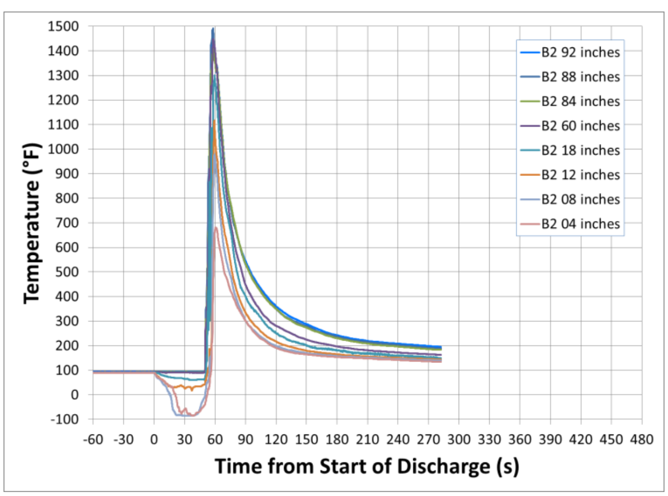
There was ignition immediately after the electric arcs were initiated, and flaming continued for another 17s. Selected data for the test are presented in Figure 52.



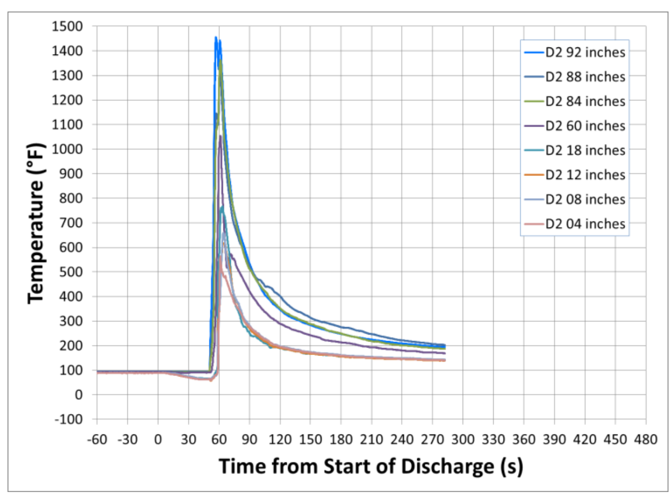
Pressure and Temperature of Release and Pressurizer Tanks



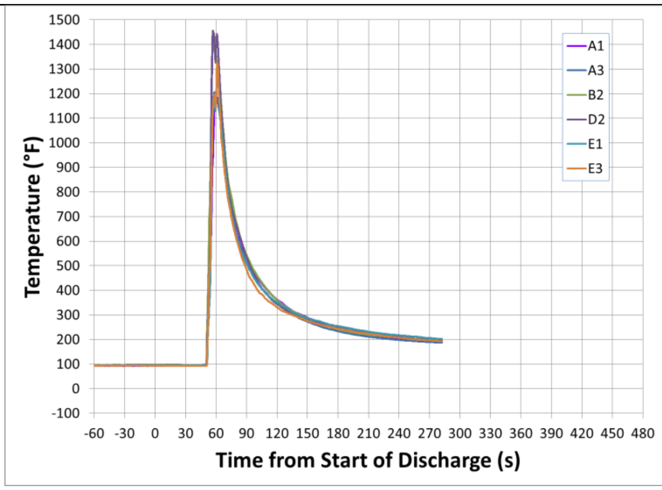
Refrigerant Release Rate



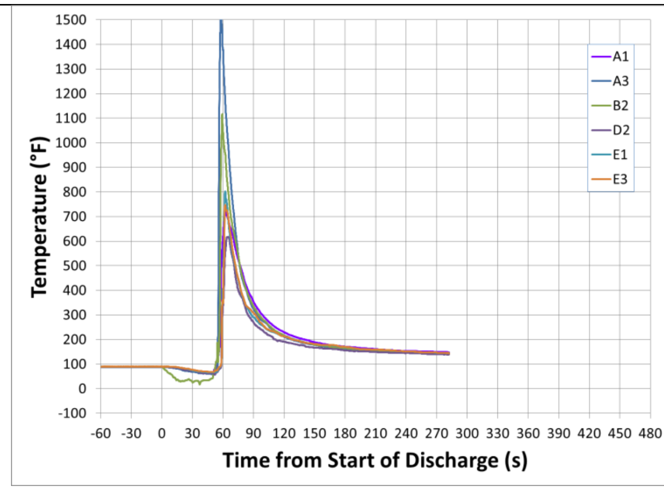
Temperature at Location B2



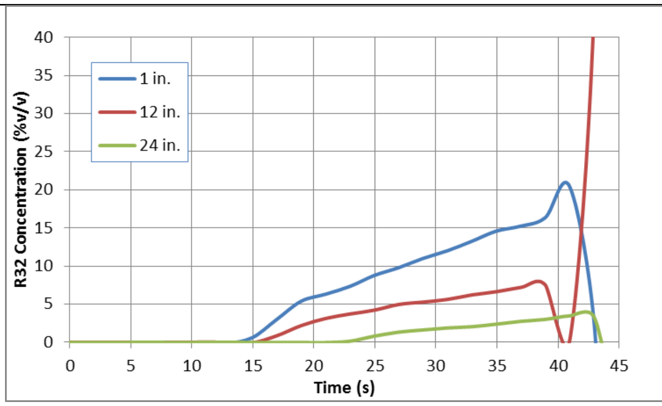
Temperature at Location D2



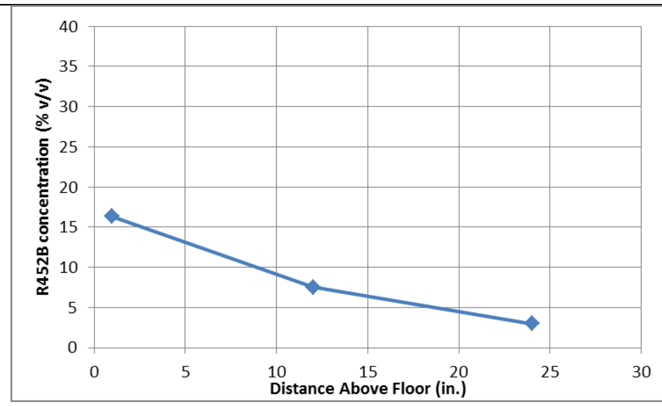
Temperature at 92 in. height above the floor



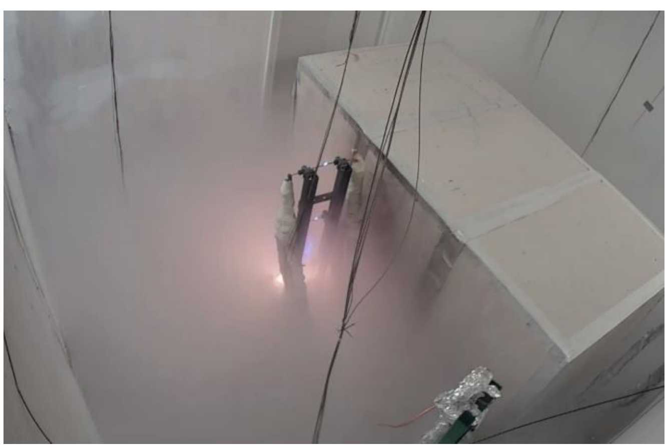
Temperature at 12 in. height above the floor



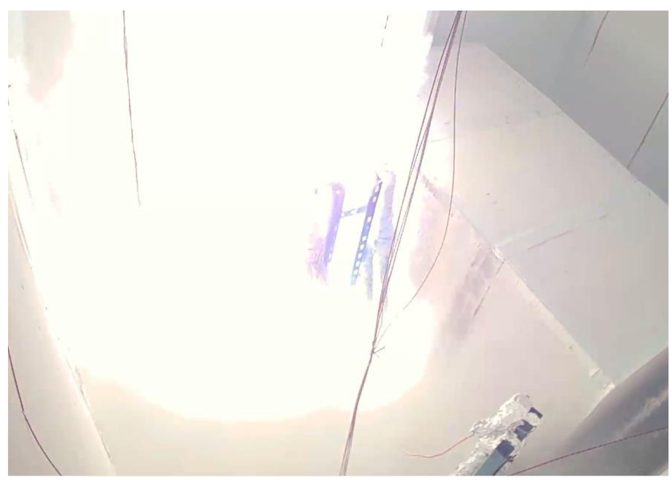
Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized



Ignition of Refrigerant when Electric arcs are Energized



2s after Ignition

Figure 52 – Data from Cal18

3.4. Parametric Testing and Results

The parametric testing was conducted to determine the influence of (i) temperature and humidity; (ii) an obstruction; (iii) the refrigerant release quantity; and (iv) lubricating oil. The influence of refrigerant release quantity was added to the scope after review of the calibration test results by the AHRTI Project Management Subcommittee (AHRTI PMS).

Table 15 – Parametric Test Conditions

Parameter	Test Conditions	Refrigerants
Temperature and Humidity	91 °F/70%RH and 73 °F/50% RH	R-32, R-452B, R-410A
Obstruction	With and without obstruction	R-32, R-452B
Lubricating Oil	0%, 1.5%, and 3.0%	R-22 with mineral oil; R-32, R-452B and R-410A with polyolester (POE) oil
Refrigerant Quantity Released	50% or 25% of LFL (when fully mixed into the nominal gross room volume)	R-32, R-452B

Based upon results from the Calibration Tests, the refrigerant release flow rate was set at 100 g/s and released from 0.2 m height through a 25 mm diameter opening in the test room.

3.4.1. Instrumentation

The instrumentation used in these tests was identical to the calibration test series.

3.4.2. Test Procedure

The following procedure was used to conduct each parametric test

1. Confirm pressure and release tank pressure and temperatures.
2. Confirm the test room temperature and humidity were as required in the test matrix with tolerances of ± 3 °F and ± 5 % RH.
3. Initiate data acquisition and video capture 1 minute prior to discharging refrigerant.
4. Develop vacuum (less than 1 mm Hg) in piping connecting the pressure and release tanks as well as between the release tank and flow meter.
5. Initiate data acquisition 60 s prior to release of refrigerant.
6. Open the valve between the pressure and release tanks, and hold for 5 s.
7. Open the valve between release tank and the flow meter and hold for 5 s.
8. Open the control valve to initiate refrigerant release through the mass flow meter. Simultaneously begin lubricating oil inject if the test calls for lubricating oil.
9. Close the release tank valve when target quantity of refrigerant has been released; discontinue sampling of refrigerant through the refrigerant sensors; open sliding deflagration door; and initiate electric arcs.
10. Continue to collect data until all flaming has ceased for at least 2 minutes.
11. Vent the test room.

After each test, the test facility was exhausted through UL’s smoke abatement system (RTO), and the conditions in the facility were monitored with open path gas FT-IR. Staff re-entered the test facility to set up the next test only after the gas FT-IR indicated normal ambient conditions.

3.4.3. Results

3.4.3.1. Influence of Ambient Temperature and Humidity

A summary of the influence of ambient temperature and humidity on ignition and flaming are presented in Table 16.

Table 16 – Summary for Influence of Temperature and Humidity

Refrigerant	Test Number	Ambient Temp and Humidity	Max Pressure (mm Hg)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	MFM Total Mass (kg)	Measured Rate (g/s)	Ignition
R-452B	PA01	73°F / 50%RH	0.15	1802	1498	3.82	98.9	Yes
R-452B	PA02	91°F / 70%RH	0.66	1805	1521	3.76	97.4	Yes
R-32	PA03	73°F / 50%RH	0.36	1479	1250	3.75	101.7	Yes
R-32	PA05	91°F / 70%RH	0.44	1492	1307	3.75	96.8	Yes
R-410A	PA04	91°F / 70%RH	0.01	95	92	3.73	100.8	No

3.4.4. Discussion of Results – Influence of Ambient Temperature and Humidity

Ignition was observed for R-32 and R-452B refrigerants with both the temperature and humidity conditions used. There was no ignition with R-410A refrigerant. It was observed from the videos that the flames in PA02 were much more energetic than PA01 which accounts for the relatively higher maximum pressure in PA02 compared to PA01.

Figure 53 shows a comparison of ambient temperature and humidity conditions on measurements in the test room.

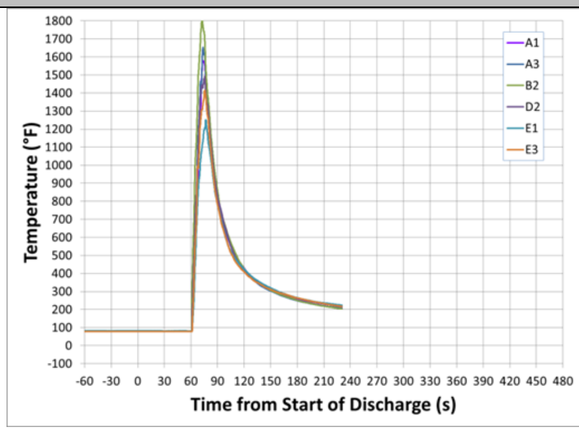
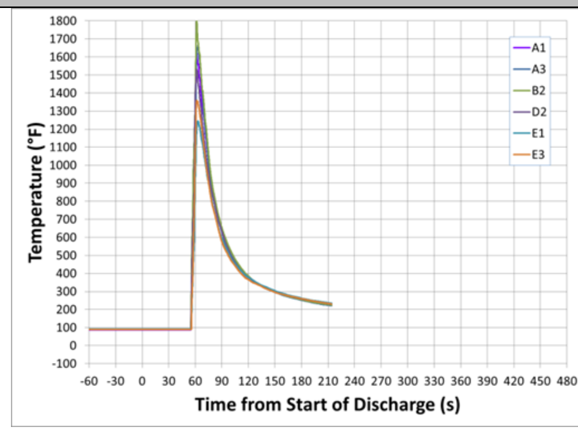
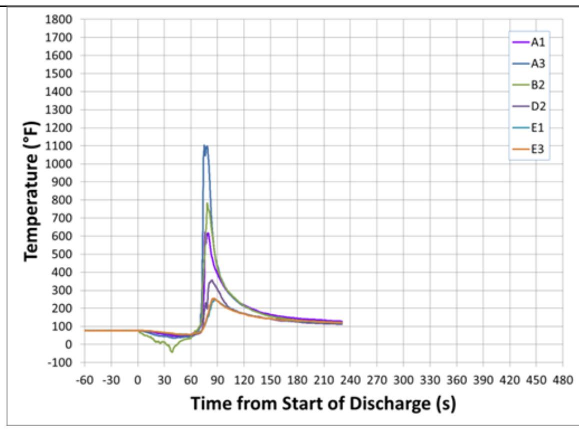
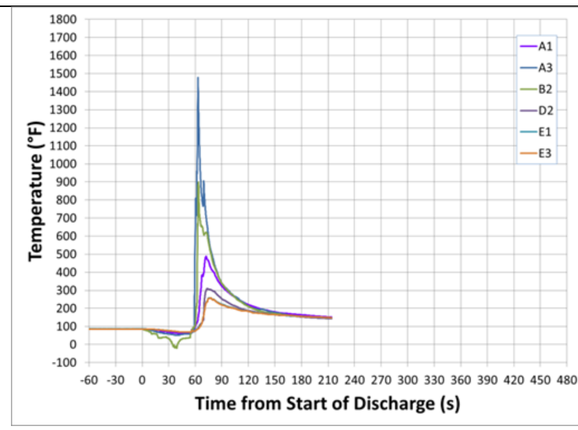
<table>
<tr><th>Measurement</th><th>70 °F and 50% RH</th><th>91 °F and 70% RH</th></tr>
<tr><td>Ceiling Temperature (92 in. above floor)</td><td>
</td><td>
</td></tr>
<tr><td>Temperature at 1 ft. above floor</td><td>
</td><td>
</td></tr>
</table>

Figure 53 – Influence of Temperature and Humidity for R-452B Refrigerant

There was not a significant difference in temperature developed in the test room after ignition had occurred. However, higher maximum pressures were recorded at 91 °F/50% RH for the refrigerants (Table 16).

Figure 54 shows the influence of ambient temperature and humidity on the measurements after ignition for R-32 refrigerant.

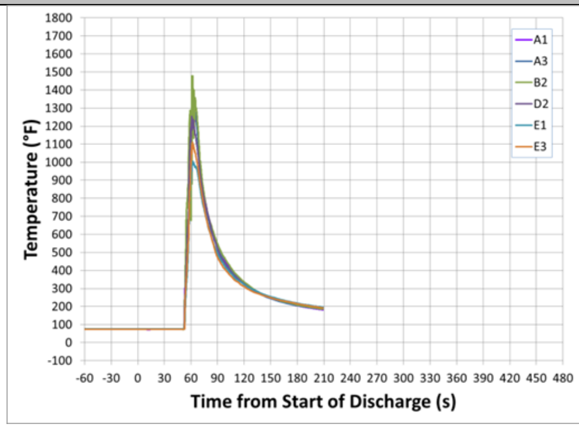
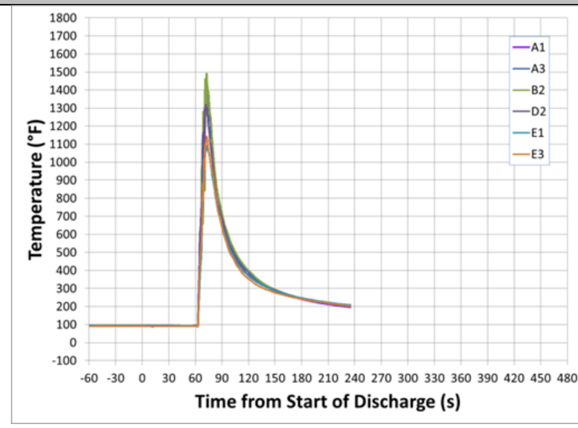
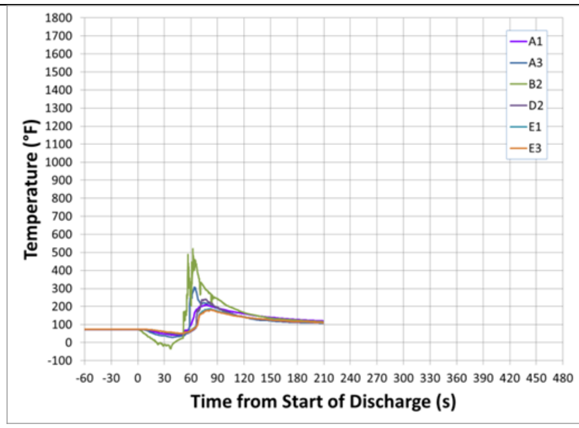
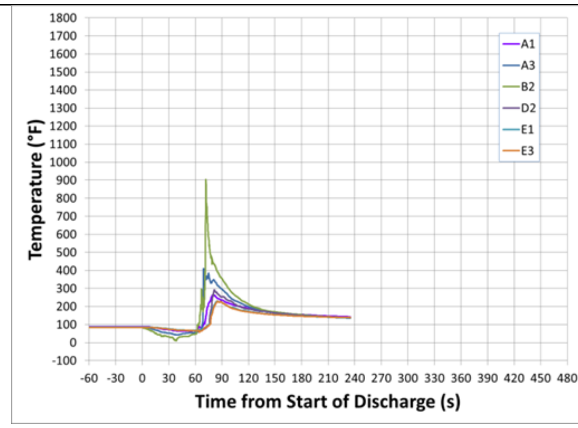
<table>
<tr><th>Measurement</th><th>70 °F and 50% RH</th><th>91 °F and 70% RH</th></tr>
<tr><td>Ceiling Temperature (92 in. above floor)</td><td>
</td><td>
</td></tr>
<tr><td>Temperature at 1 ft. above floor</td><td>
</td><td>
</td></tr>
</table>

Figure 54 – Influence of Ambient Temperature and Humidity for R-32 Refrigerant

There was not a significant difference in temperature developed in the test room after ignition had occurred. The fire duration at 91 °F/70 %RH was longer than at 70 °F/50%RH. (35s versus 21s).

For both of the refrigerants, maximum pressures were recorded at 91 °F/50% RH were higher (Table 16).

3.4.4.1. *Influence of Obstruction*

Tests were conducted with refrigerants with and without the obstruction. The influence of obstruction was investigated with 91 °F and 70%RH since these test conditions tests resulted greater intensity of flaming.

A summary of results are presented in Table 17.

Table 17 – Influence of Obstruction

Refrigerant	Test Number	Obstruction	Max Pressure (mm Hg)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	MFM Total Mass (kg)	Measured Rate (g/s)	Ignition
R-32	PB01	Yes	0.39	1500	1367	3.89	82.0	Yes
R-452B	PB02	Yes	0.63	1503	1350	3.84	98.1	Yes
R-452B	PB03	No	0.02	295	248	3.81	104.0	Yes
R-32 [1]	PB04	No	0.29	>2300	1359	3.71	62.0	Yes
R-410A	PB05	No	0.01	104	101	3.70	63.4	No
R-32	PB12	No	0.01	101	99	3.49	98.7	No

Note: [1] The test did not achieve control of flow rate and was repeated as test PB12

3.4.4.1.1. Discussion of Results – Influence of Obstruction

Tests with the obstruction resulted in ignition for both R-32 and R-452B refrigerant. As observed in the calibration test, the obstruction breaks up the refrigerant flow and mixes with the air to create a flammable mixture. Without the obstruction, the release jet mixes with the air and is diluted.

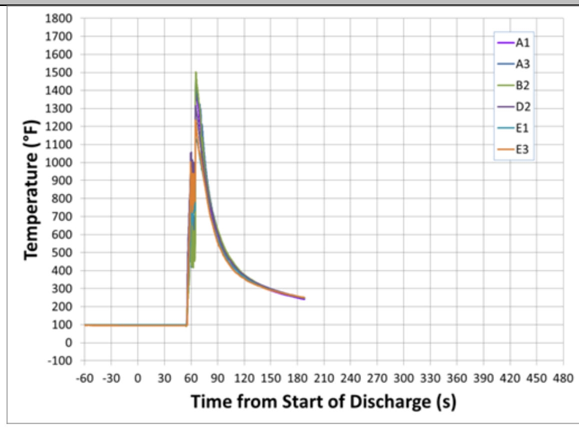
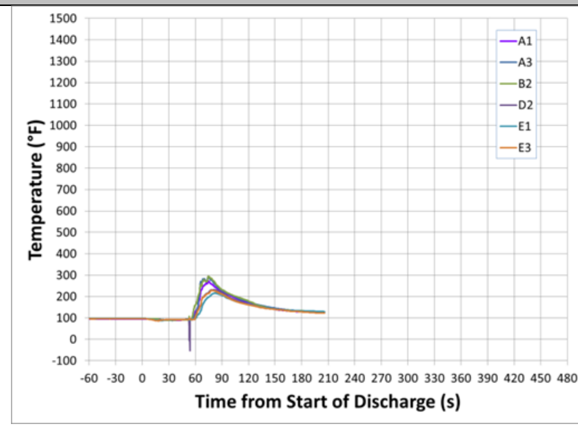
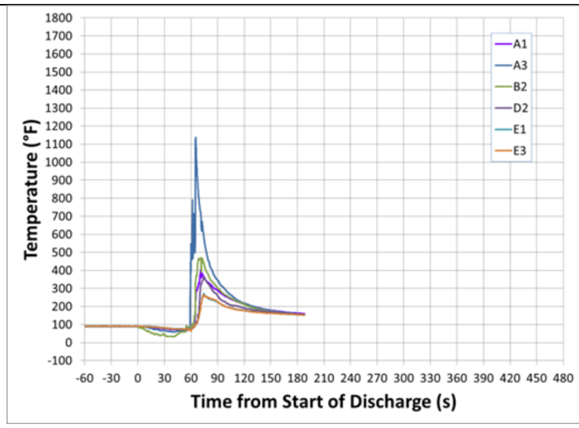
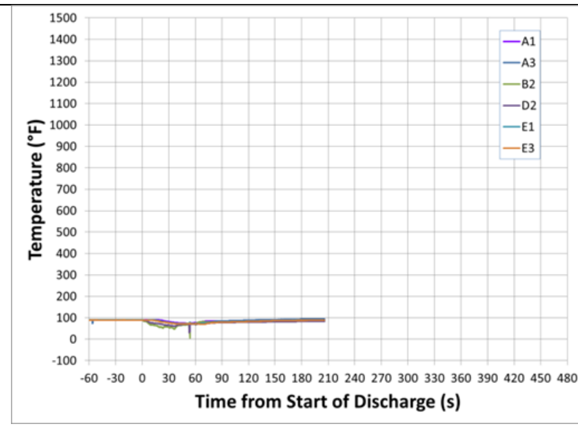
For R-32 refrigerant there was ignition of the released refrigerant with the obstruction. Without the obstruction, the refrigerant flow rate influenced the mixing with test room air. In test PB04, video showed that the refrigerant did not completely traverse the room length and mixed less with room air. In test PB12, the refrigerant flow can be seen to traverse the room length, strikes the opposite wall and mixes well with room air.

For R-452B refrigerant, the refrigerant ignited but the resulting temperatures and pressure increase in the room as well as fire size (from video) without obstruction was significantly smaller than with obstruction.

For R-410A refrigerant, there was no ignition of the released refrigerant without obstruction. Results from tests to investigate the influence of ambient temperature and humidity, showed that R-410A (PA04) did not ignite with obstruction.

Selected data for R-452B and R-32 tests are presented herein for comparison.

Figure 55 shows the temperature and photographic data for R-452B refrigerant with and without obstruction.

<table>
<tr><th>Measurement</th><th>Obstruction</th><th>No Obstruction</th></tr>
<tr><td>Ceiling Temperature (92 in. above floor)</td><td>
</td><td>
</td></tr>
<tr><td>Temperature at 1 ft. above floor</td><td>
</td><td>
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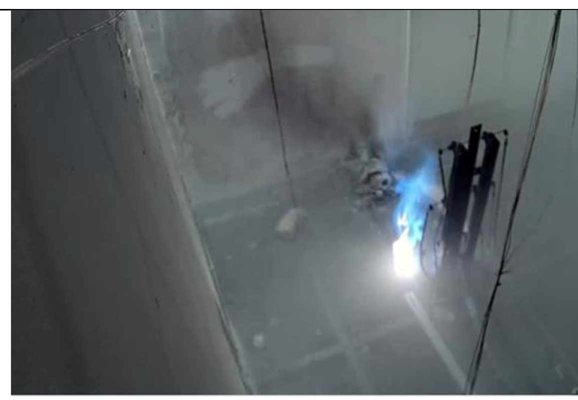
<tr><td>Fire Size</td><td></td><td></td></tr>
</table>

Figure 55 – Influence of Obstruction for R-452B Refrigerant

Figure 56 shows the temperature and photographic data for R-32 refrigerant with and without obstruction.

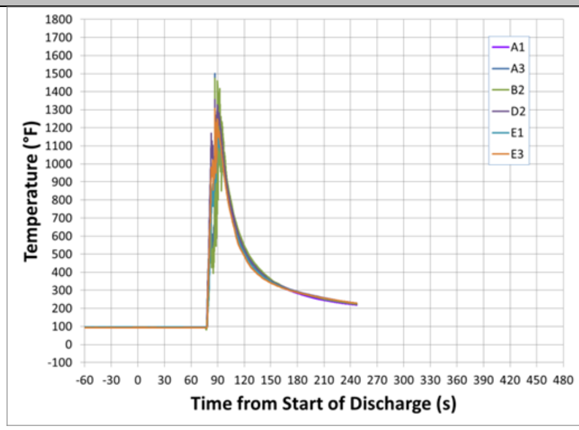
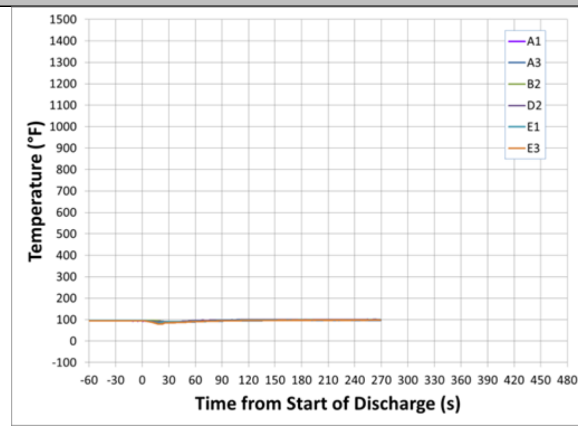
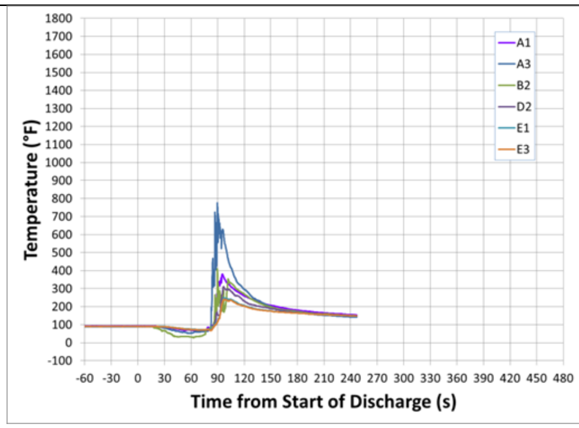
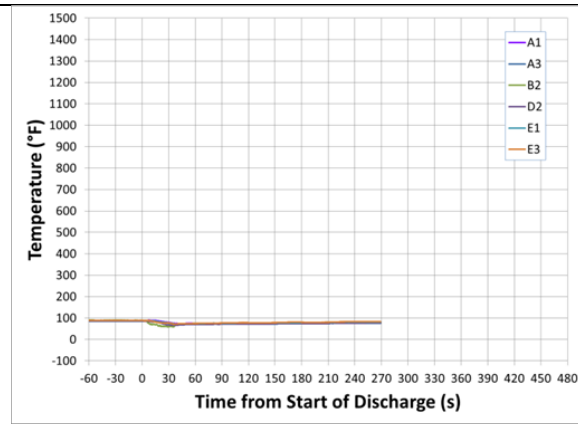
Measurement	Obstruction	No Obstruction
Ceiling Temperature (92 in. above floor)		
Temperature at 1 ft. above floor		
Fire Size		 No Ignition

Figure 56 – Influence of Obstruction for R-32 Refrigerant

Note that test PB04 was an R-32 refrigerant release with no obstruction in the room. There was an ignition. Since the release rate was only two-thirds of the intended release rate, it was not used for the graphs shown above. There was ignition and flaming (Figure 57) continued for 25 seconds after ignition.

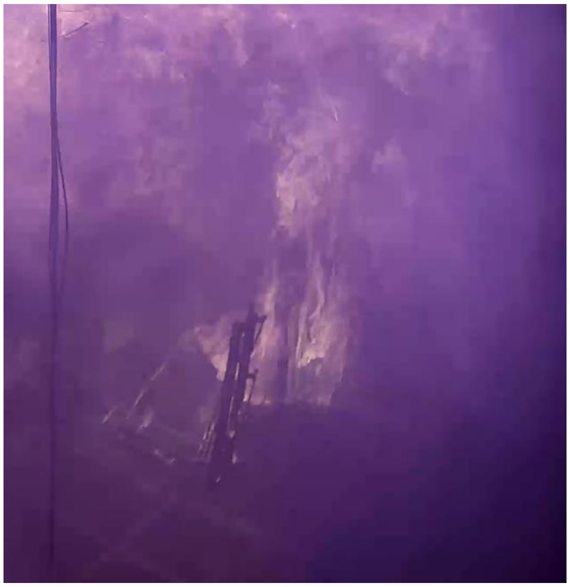


Figure 57 – Flaming in test PB04 with two-thirds of planned flow rate

3.4.4.2. *Influence of Refrigerant Quantity Released and Obstruction*

Tests were conducted to determine the influence of refrigerant quantity released. From the tests listed in Table 17, the total refrigerant quantity released was reduced from 50% to 25% of the lower flammability limit (assuming the mixture was completely mixed in the room). A summary of results are presented in Table 18. These tests were conducted with and without obstruction.

Table 18 – Influence of Refrigerant Quantity and Obstruction

Refrigerant	Test Number	Obstruction and Refrigerant Quantity	Release Opening Diameter (mm)	Release Height (m)	Max Pressure (mm Hg)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	MFM Total Mass (kg)	Measured Rate (g/s)	Ignition
R-32	PB08	No Obstruction; 25% of LFL	25	0.2	0.01	98	96	1.94	96.6	No
R-452B	PB09	No Obstruction; 25% of LFL	25	0.2	0.01	96	94	1.87	97.8	No
R-32	PB10	Obstruction; 25% of LFL	25	0.2	0.01	221	172	1.77	96.1	Yes
R452B	PB11	Obstruction; 25% of LFL	25	0.2	0.01	121	106	1.80	97.8	Yes
R-32	CAL20	Obstruction; 25% of LFL	356	2.2	0.01	93	91	1.93	93.8	No

3.4.4.2.1. Discussion of Results – Influence of Refrigerant Quantity and Obstruction

Results from 25 mm diameter release opening: Release of R-32 and R-452B to achieve a concentration equal to 25% of their LFL values did not result ignition without the obstruction. However, both refrigerants resulted in ignition at that concentration with obstruction present. The temperature and fire size observed with lower concentration were smaller than tests with concentrations equal to 50% of LFL values with the ignition of refrigerant localized to area of ignition sources.

Results from 356 mm diameter release opening: One test (Cal20) was conducted with R-32 refrigerant released from the 356 mm diameter duct with obstruction to determine the influence of flow velocity on ignition. Ignition was not observed under these conditions.

A comparison of results for R-452B refrigerant is presented in Figure 58.

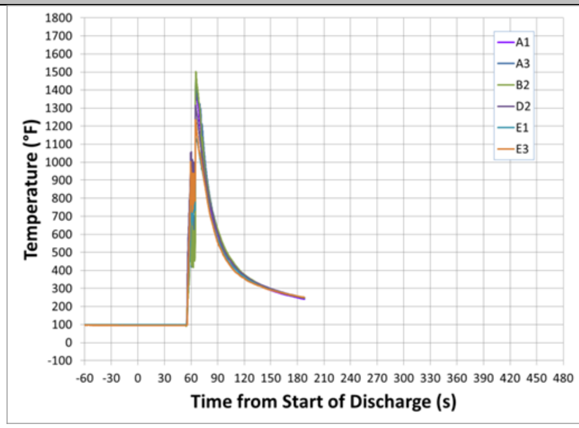
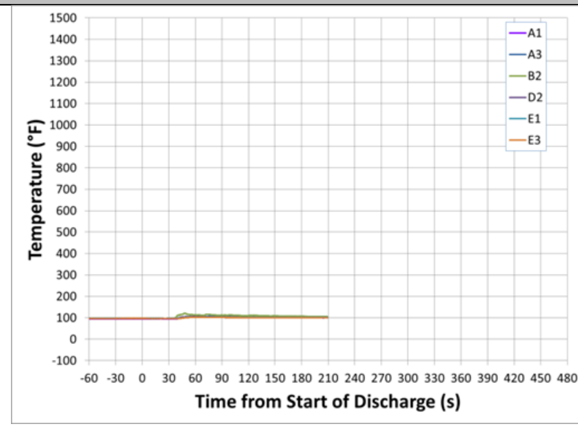
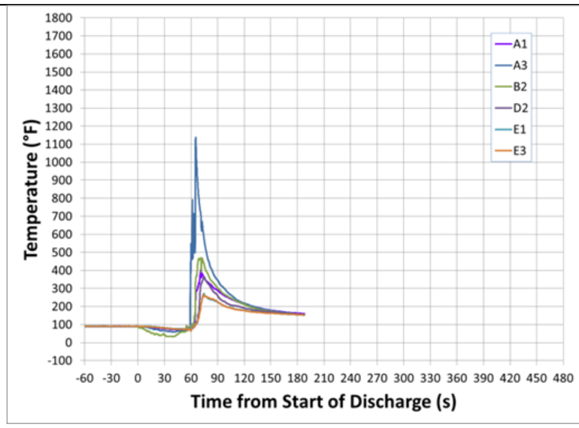
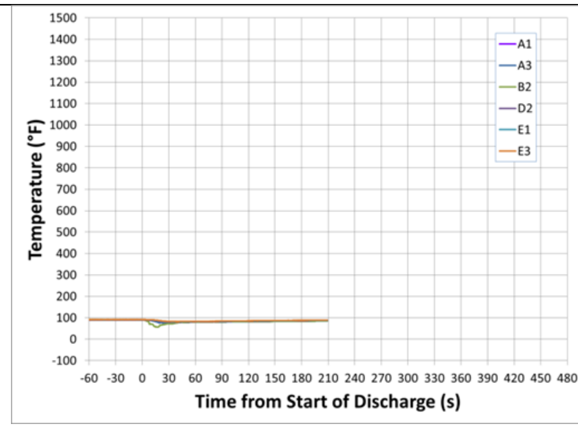
Measurement	50% LFL	25% LFL
Ceiling Temperature (92 in. above floor)		
Temperature at 1 ft. above floor		
Fire Size		

Figure 58 – Comparison of Released Refrigerant Quantity for R-452B Refrigerant

A comparison of results for R-32 refrigerant released from 25 mm diameter tubing is presented in Figure 59.

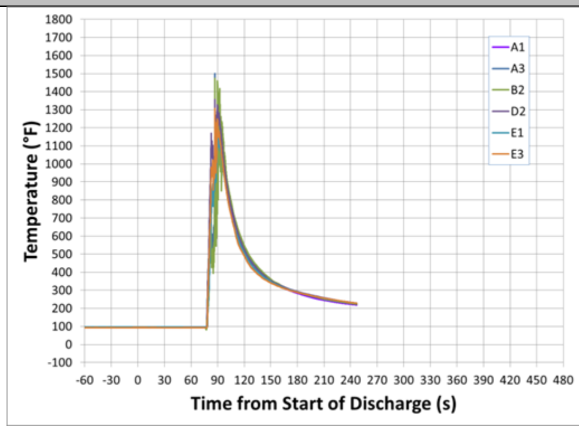
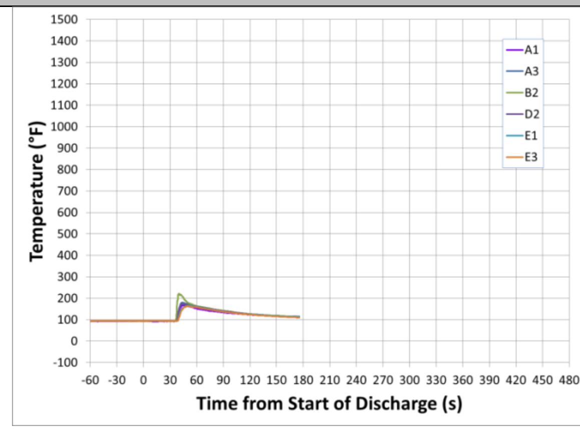
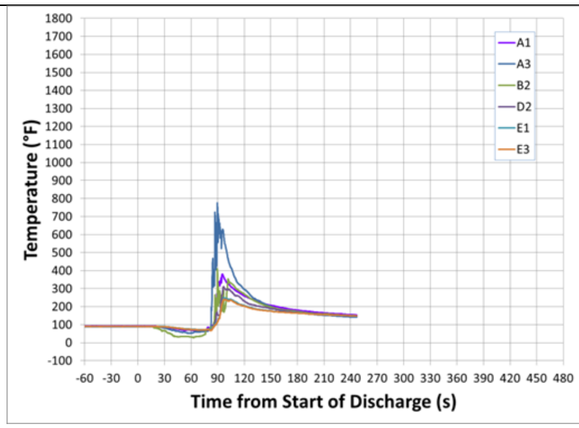
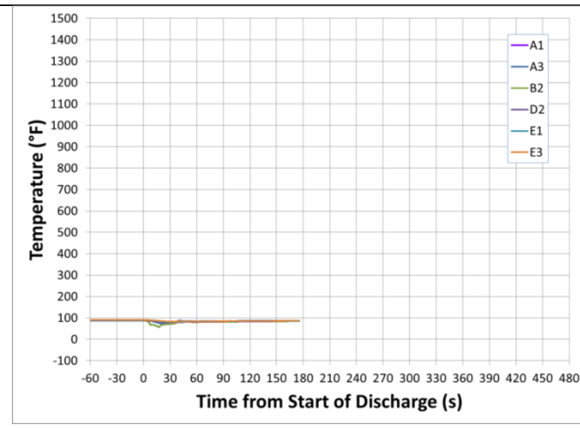
<table>
<tr><th>Measurement</th><th>50% LFL</th><th>25% LFL</th></tr>
<tr><td>Ceiling Temperature (92 in. above floor)</td><td>
</td><td>
</td></tr>
<tr><td>Temperature at 1 ft. above floor</td><td>
</td><td>
</td></tr>
<tr><td>Fire Size</td><td></td><td></td></tr>
</table>

Figure 59 - Comparison of Released Refrigerant Quantity for R-32 Refrigerant

3.4.4.3. Influence of Lubricating Oil

Tests were conducted to determine the influence of lubricating oil on ignition and flaming of the refrigerants. A polyolester oil (POE oil) was used for R-32, R-452B, and R-410A refrigerants, and a mineral oil was used for R-22 refrigerant.

These tests series were performed with a target refrigerant flow rate of 100 g/s from a 25 mm opening located at a height of 0.2m. The lubricating oil was metered into the refrigerant between the mass flow meter and flow controller at a constant rate using a positive displacement pump.

All the tests were performed without obstruction, since both R-32 and R-452B ignited without obstruction in calibration and parametric tests. A summary of results is presented in Table 19.

Table 19 – Influence of Lubricating Oil

Refrigerant	Test Number	Lubricating Oil Quantity	Max Pressure (mm Hg)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	MFM Total Mass (kg)	Measured Rate (g/s)	Ignition
R-410A	PC07	1.5%	0.01	101	99	3.36	75.3	No
R-410A	PC08	3.0%	0.01	99	97	3.30	81.3	No
R-32	PC10	1.5%	0.35	1677	1338	3.86	97.3	Yes
R-32	PC11	3.0%	0.01	134	110	3.62	98.8	Yes
R-22	PC12	1.5%	0.01	99	97	4.12	99.1	No
R-22	PC13	3.0%	0.01	100	98	4.26	90.3	No
R-452B	PC14	3.0%	0.02	97	95	3.53	95.4	No
R-452B	PC15	1.5%	0.01	98	96	3.51	90.0	No

3.4.4.3.2. Discussion of Results - Influence of Lubricating Oil

There was no ignition of the refrigerant for R-410A and R-22 refrigerants with both 1.5% and 3.0% oil quantity. There was also no ignition for R-452B refrigerants with either 1.5% or 3.0% oil quantity. However, R-32 released with 1.5% oil quantity resulted in a significant fire with maximum ceiling temperature exceeding 1600 °F. The fire engulfed the area of the electric arcs, and then spread across the floor toward the release wall. In the test with 3.0% oil quantity, the fire was relatively small and blue in color.

In earlier tests, it was observed that R-452B ignited under the same discharge conditions (test numbers Cal18, PA02, PB03), but without oil injection. Additional investigation is needed to trace the cause of this effect. Areas of additional investigation may include the following:

- Repeatability of the refrigerant release method (variations in concentration profile versus time and variation in total refrigerant quantity released),
- The size of oil droplets in the discharge,
- The degree of mixing of oil in the refrigerant flow,
- The effect of the discharge on the electric arcs,
- The difference in density between R-452B and R-32, and
- The ignitability of various refrigerant oil mixtures in an electric arc.

Analysis of the R-452B and R-32 videos shows a difference in the oil spray pattern on the test room floor.

A comparison of the data for R-32 refrigerant with 1.5% and 3.0% oil quantity is presented in Figure 60.

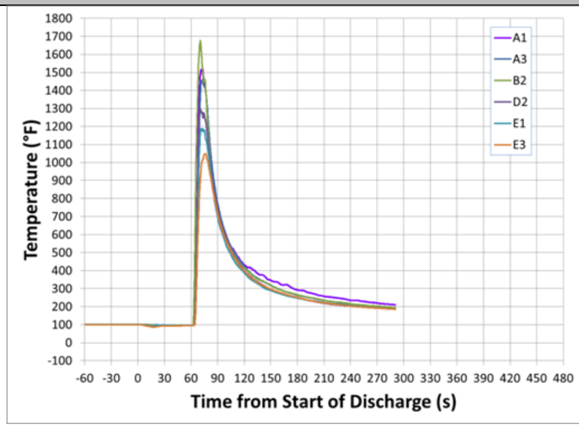
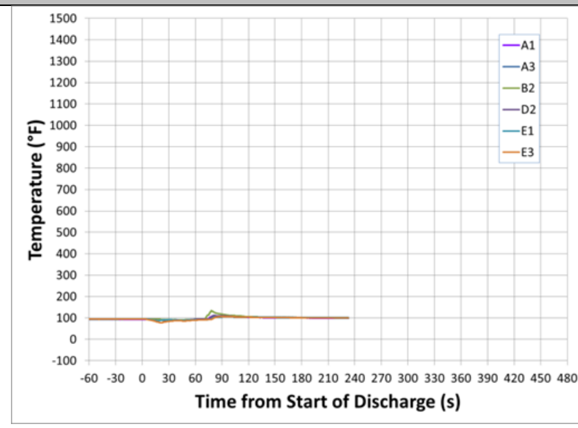
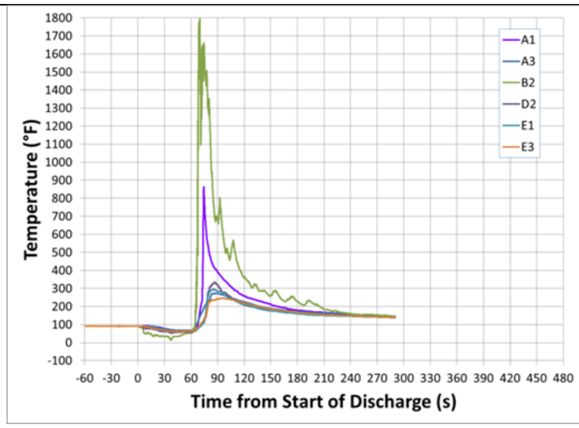
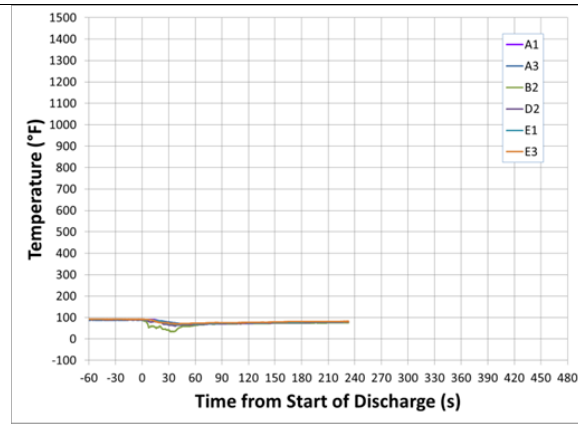
Measurement	1.5% Lubricating Oil	3.0 % Lubricating Oil
Ceiling Temperature (92 in. above floor)		
Temperature at 1 ft. above floor		
Fire Size		

Figure 60 – Comparison of Results for R-32 Refrigerant with Lubricating Oil

3.4.5. Summary of Findings from Parametric Tests

1. Refrigerants R-22, and R-410A with lubricating oil (1.5 and 3.0%) did not ignite under the test conditions used in this investigation.
2. Ignition of R-32 in higher ambient temperature and humidity conditions (91 °F and 70 % RH) resulted in higher maximum pressure in the test room, and longer duration fire for R-32 refrigerant.
3. Ignition of R-452B in lower temperature and humidity conditions (73 °F and 50 % RH) resulted in higher maximum temperature in the test room, but the duration of flaming was longer. Ignition of R-452B at 91°F and 70% RH resulted in a higher pressure rise.
4. The presence of the obstruction in the room increases mixing of the refrigerant release with room air. However, this appears to develop local conditions that have a flammable refrigerant mixture that is above the LFL and conducive to ignition. The volume of the obstruction was not used to reduce the volume of the room in calculating the planned refrigerant discharge amount.
5. In general, reducing the refrigerant quantity to achieve average room concentration equal to 25% LFL, and with obstruction, reduced the fire size and temperatures observed in the room. Further, the fire was localized to the area of the ignition source. Without the obstruction, ignition did not occur for either R-32 or R-452B refrigerant.
6. R-452B tests with lubricating oil (1.5 and 3.0%) and no obstruction did not result in ignition. R-452B refrigerant tested without lubricating oil and with no obstruction did result in ignition.
7. R-32 refrigerant ignited with a significant fire with 1.5% lubricating oil and no obstruction, but had a relatively small fire with 3.0% lubricating oil.

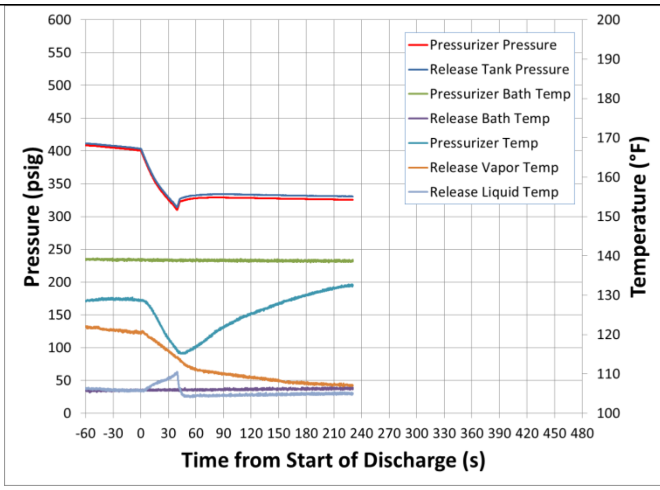
3.4.6. Test Observations, Temperature, Refrigerant Concentration and Video Documentation for Parametric Tests

3.4.6.1. Influence of Ambient Temperature and Humidity

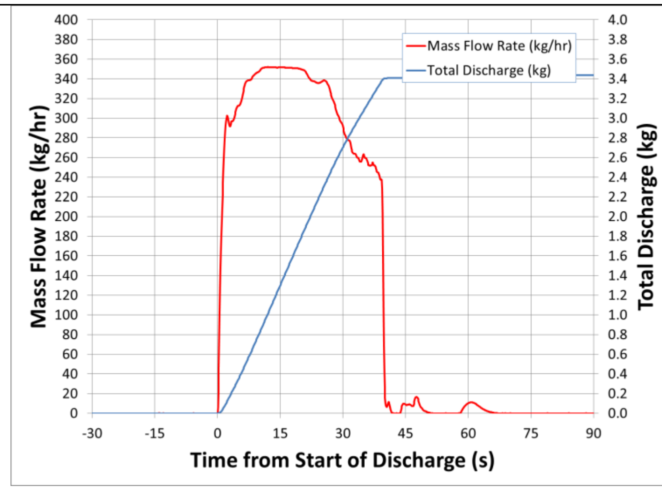
Test PA01: The parameters for the test were as follows:

Refrigerant	Temperature and Humidity	Ignition Result
R-452B	73°F / 50%RH	Ignition

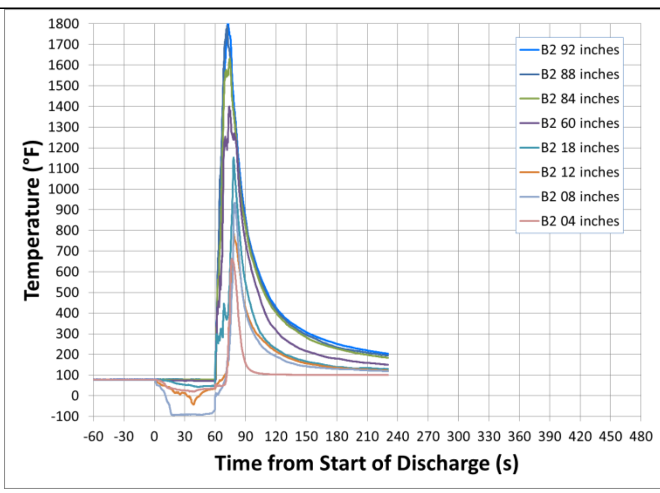
There was ignition immediately after the electric arcs were initiated, and the flaming continued for another 23s. Selected data for the test are presented in Figure 61.



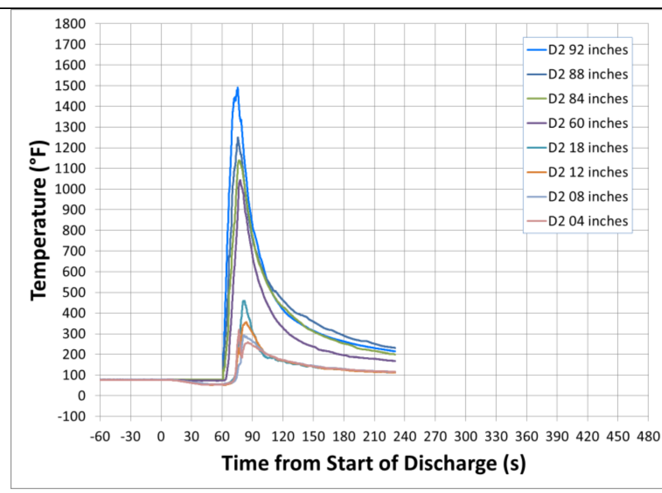
Pressure and Temperature of Release and Pressurizer Tanks



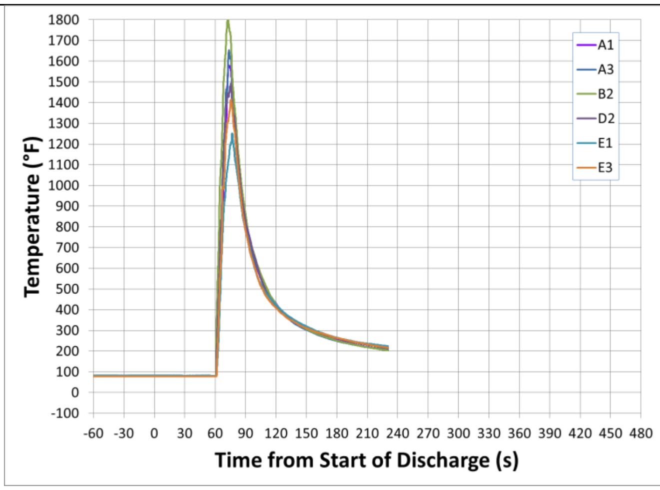
Refrigerant Release Rate



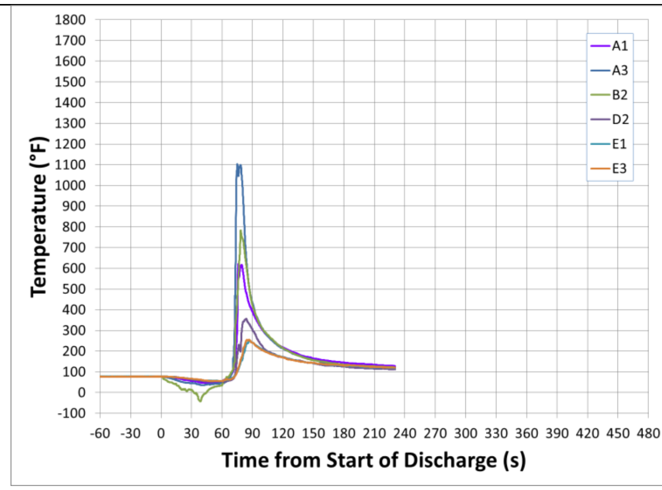
Temperature at Location B2



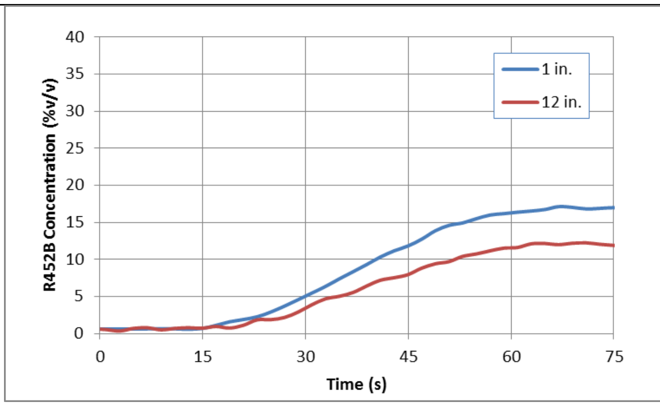
Temperature at Location D2



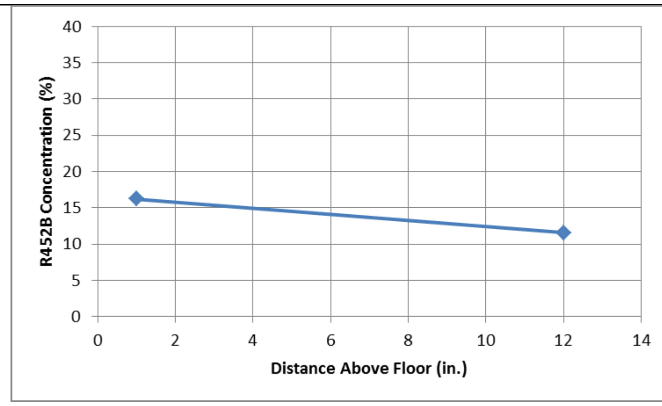
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor

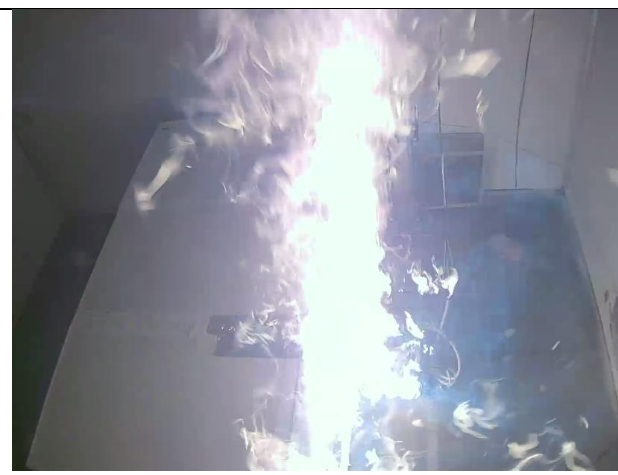


Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

Ignition of Refrigerant when Electric arcs are Energized



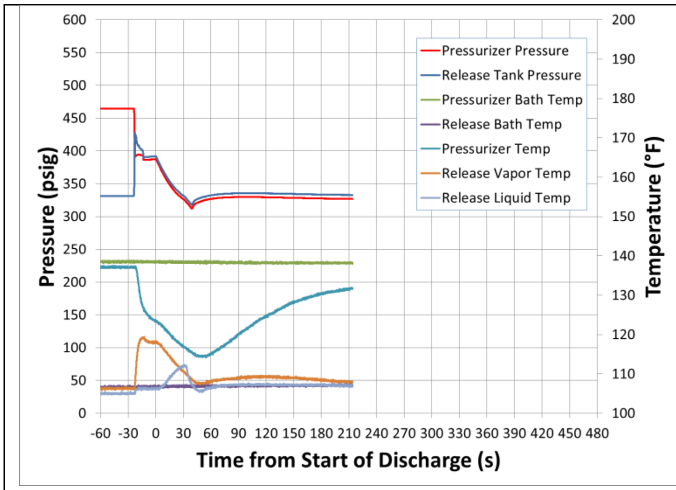
10s after Ignition

Figure 61 – Data for PA01

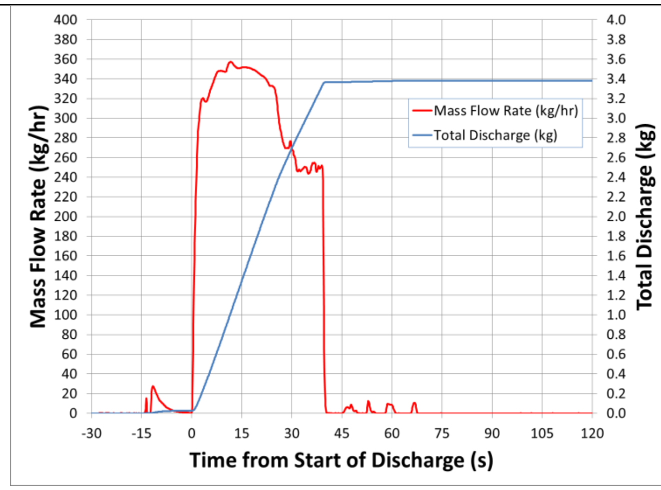
Test PA02: The parameters for the test were as follows:

Refrigerant	Temperature and Humidity	Ignition Result
R-452B	91°F / 50%RH	Ignition

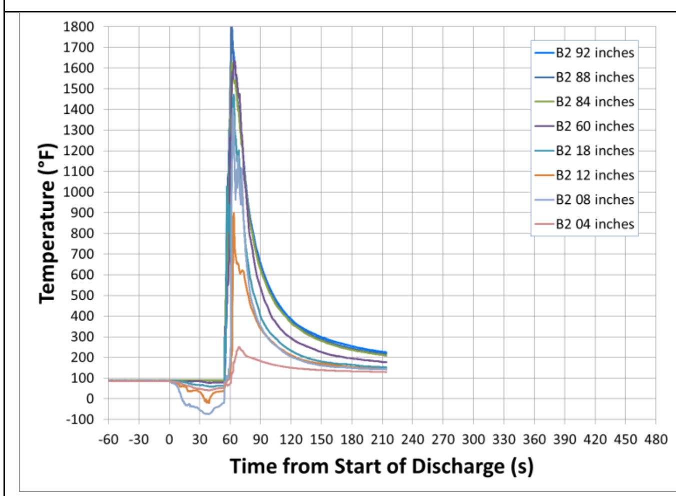
There was ignition immediately after the electric arcs were initiated, and the flaming continued for another 28s. Selected data for the test are presented in Figure 62.



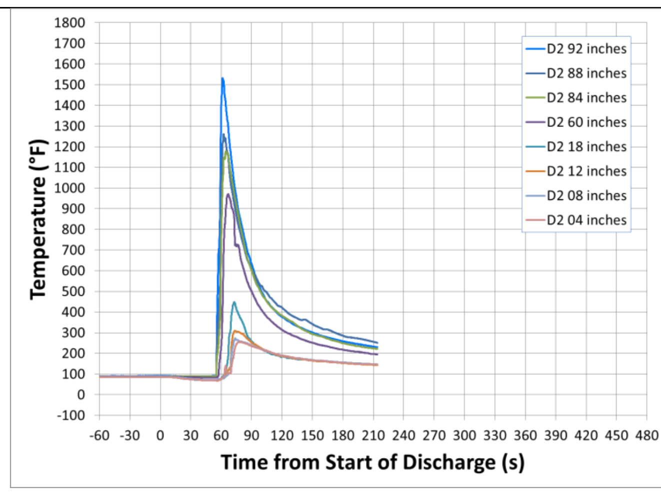
Pressure and Temperature of Release and Pressurizer Tanks



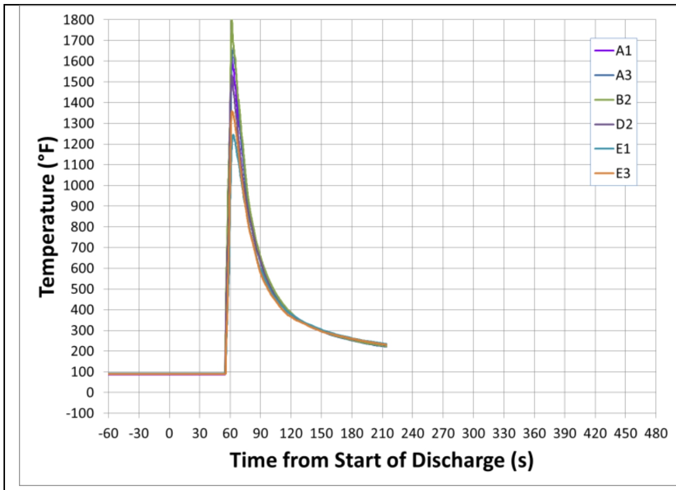
Refrigerant Release Rate



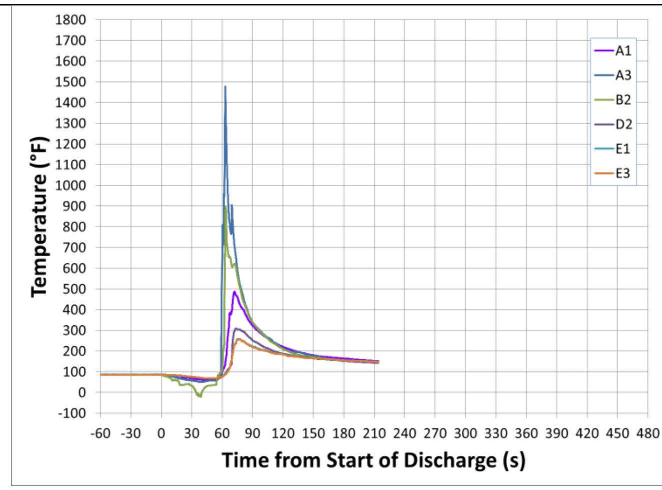
Temperature at Location B2



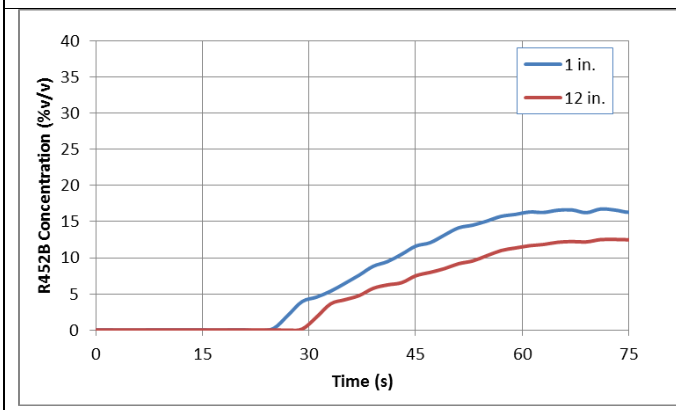
Temperature at Location D2



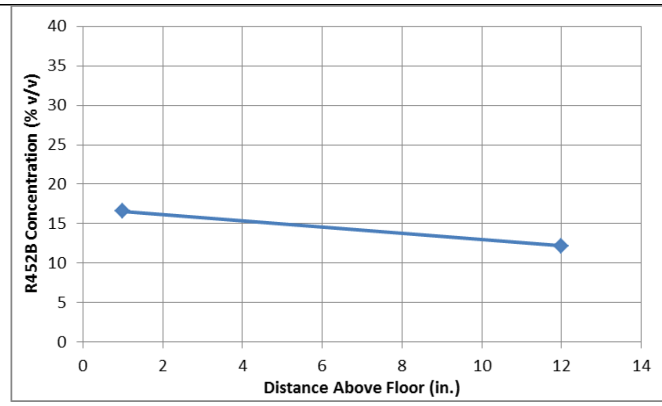
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

Ignition of Refrigerant when Electric arcs are Energized

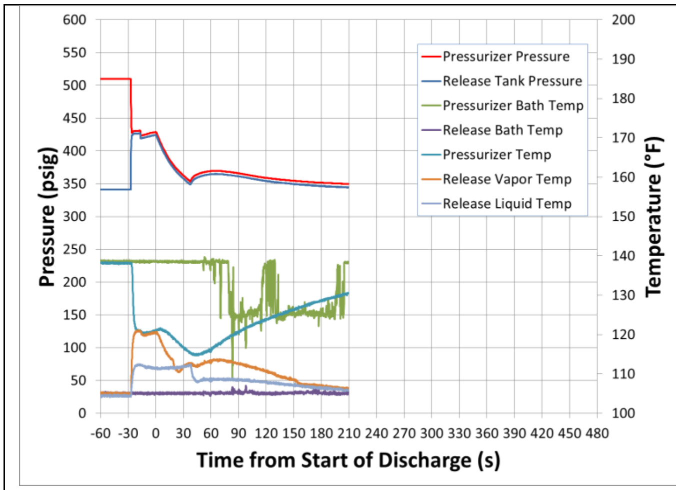
10s after Ignition

Figure 62 – Data for PA02

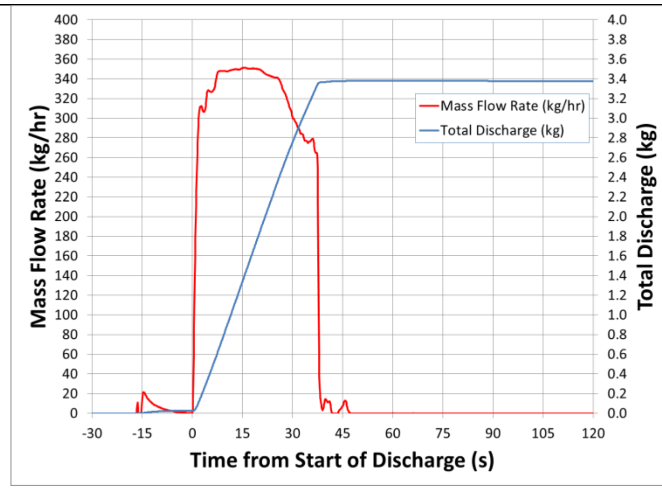
Test PA03: The parameters for the test were as follows:

Refrigerant	Temperature and Humidity	Ignition Result
R-32	70°F / 50%RH	Ignition

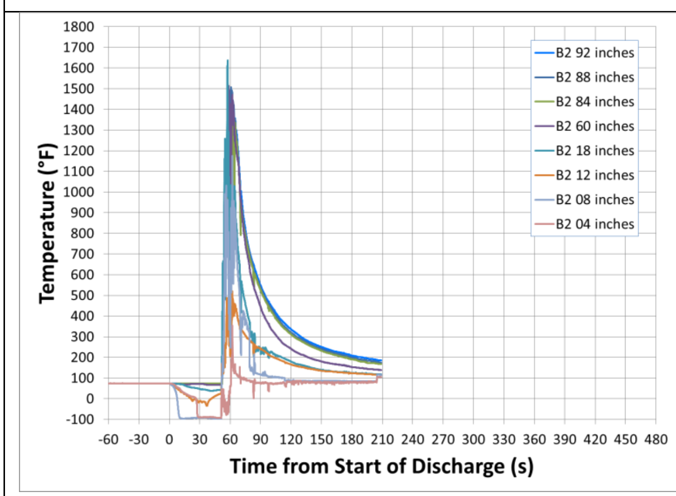
There was ignition immediately after the electric arcs were initiated, and the flaming continued for another 21s. Selected data for the test are presented in Figure 63.



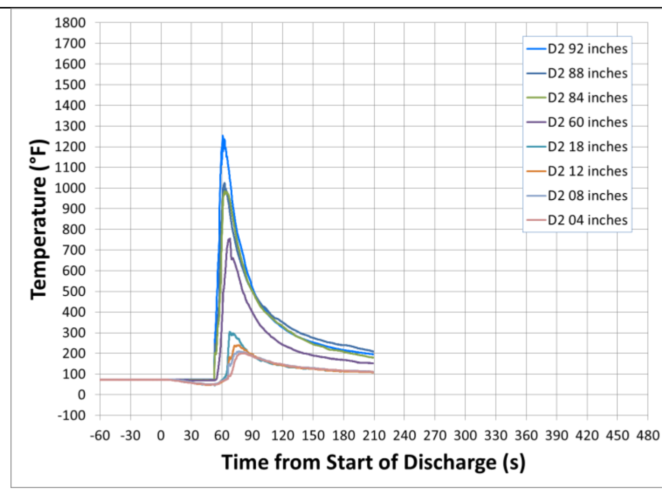
Pressure and Temperature of Release and Pressurizer Tanks



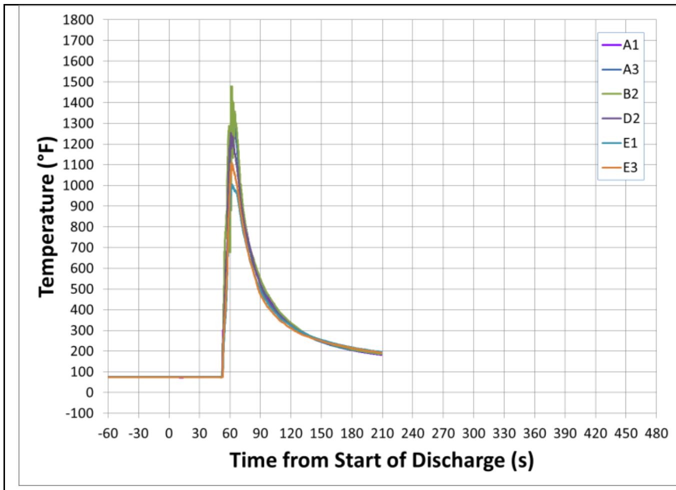
Refrigerant Release Rate



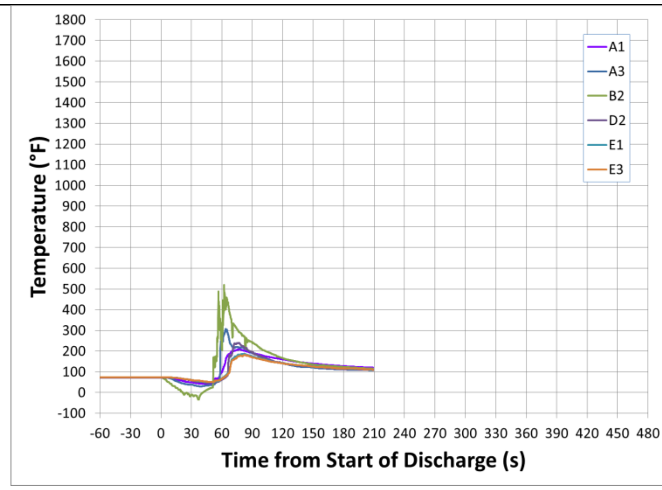
Temperature at Location B2



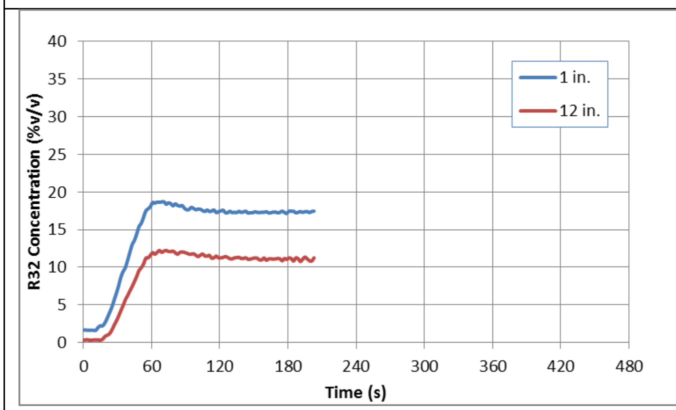
Temperature at Location D2



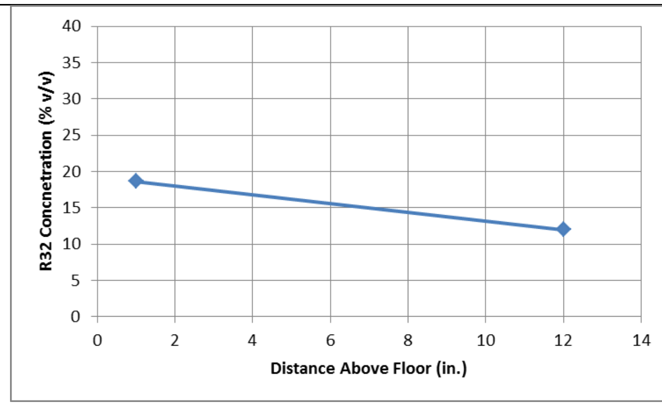
Temperature at 92 in. height above the floor



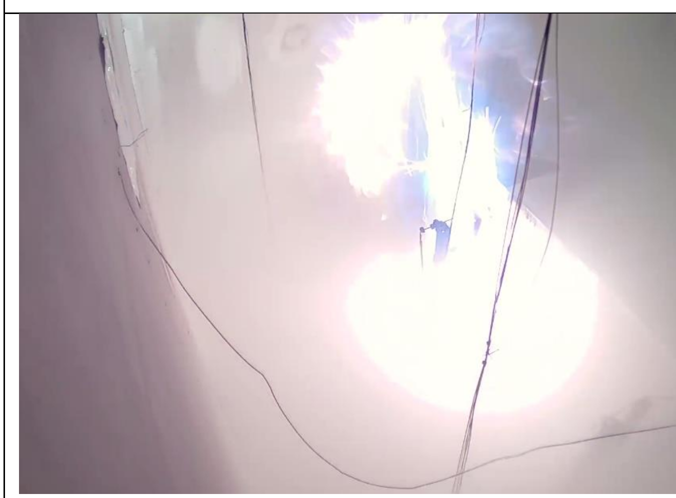
Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized



Ignition of Refrigerant when Electric arcs are Energized

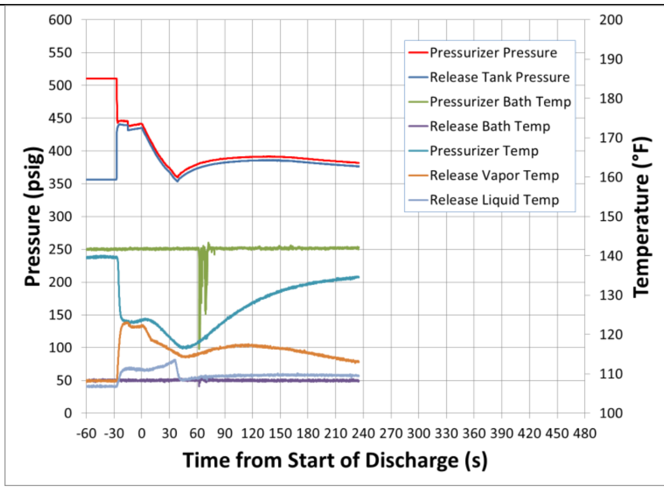
5s after Ignition

Figure 63 – Data for PA03

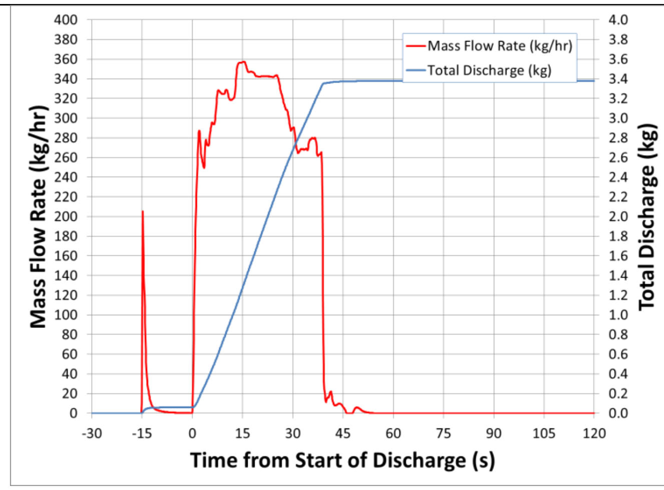
Test PA05: The parameters for the test were as follows:

Refrigerant	Temperature and Humidity	Ignition Result
R-32	91°F / 70%RH	Ignition

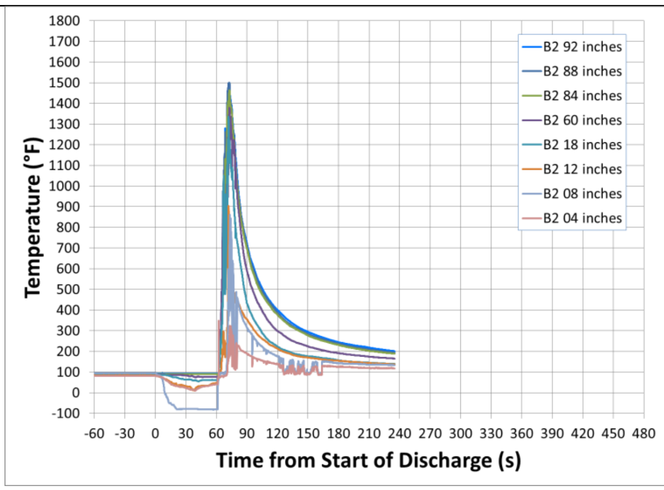
There was ignition immediately after the electric arcs were initiated, and the flaming continued for another 32s. Selected data for the test are presented in Figure 64.



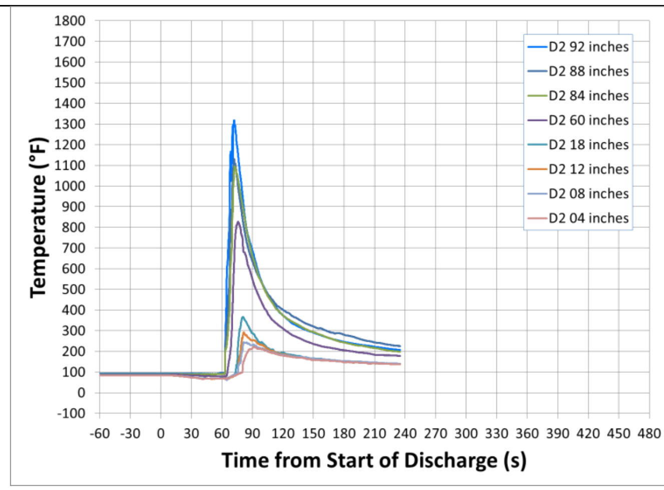
Pressure and Temperature of Release and Pressurizer Tanks



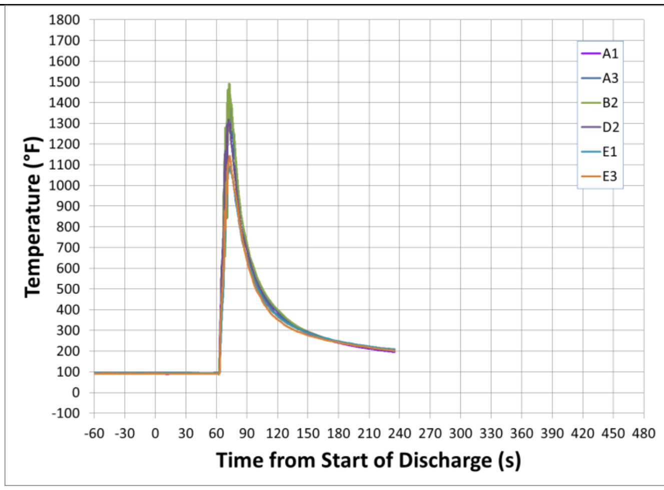
Refrigerant Release Rate



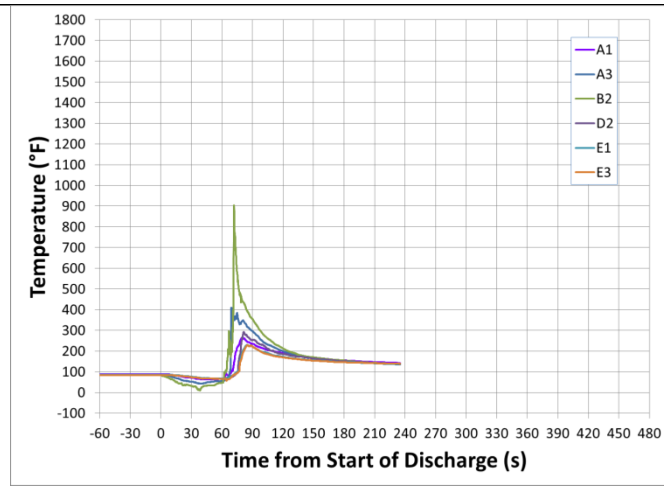
Temperature at Location B2



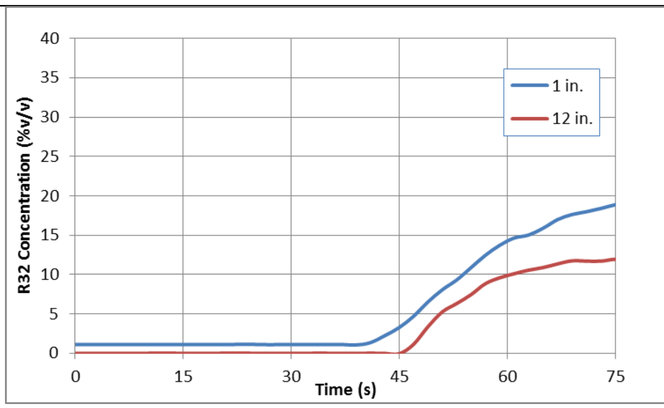
Temperature at Location D2



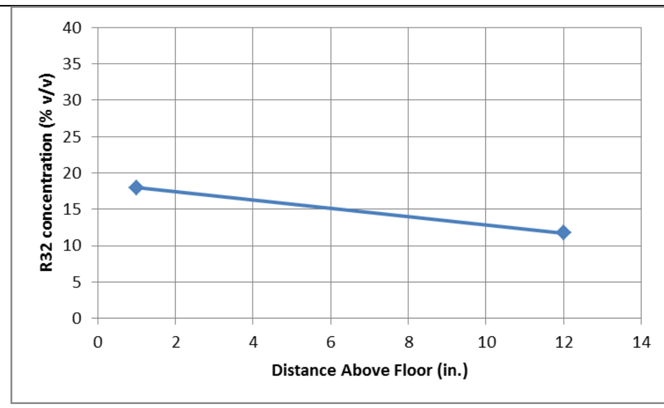
Temperature at 92 in. height above the floor



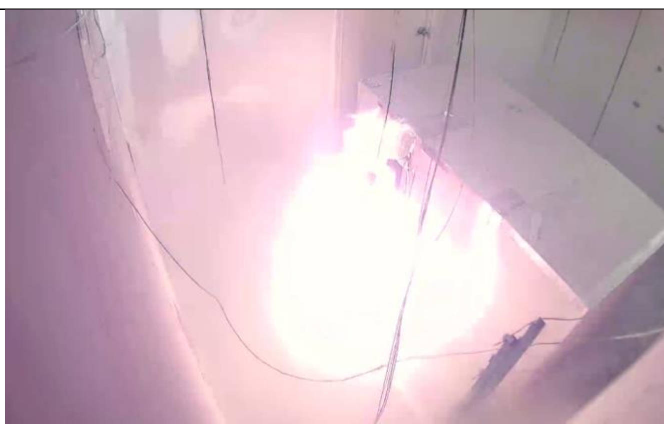
Temperature at 12 in. height above the floor



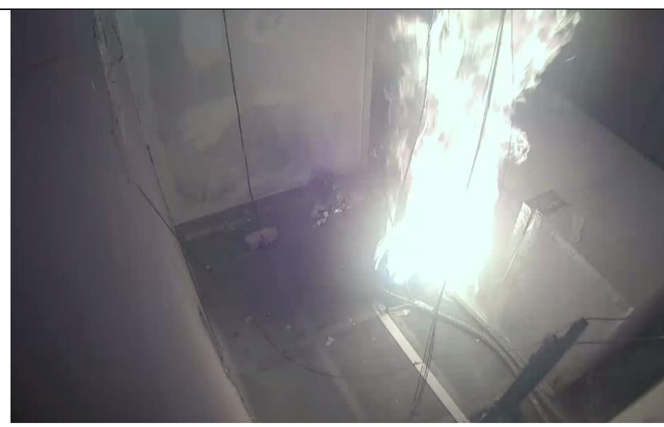
Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized



Ignition of Refrigerant when Electric arcs are Energized



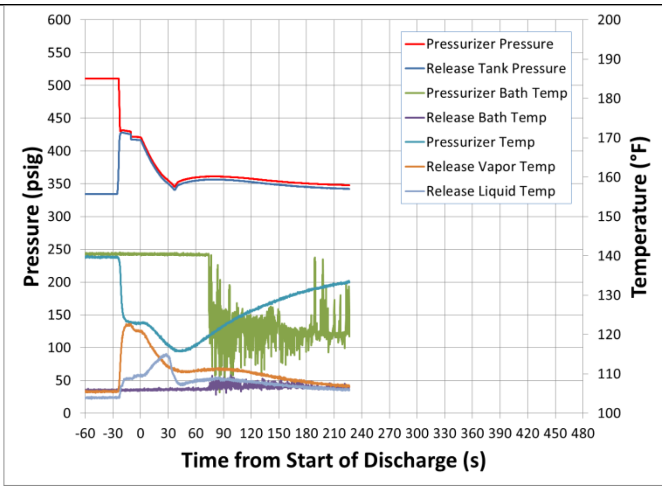
5s after Ignition

Figure 64 – Data for PA05

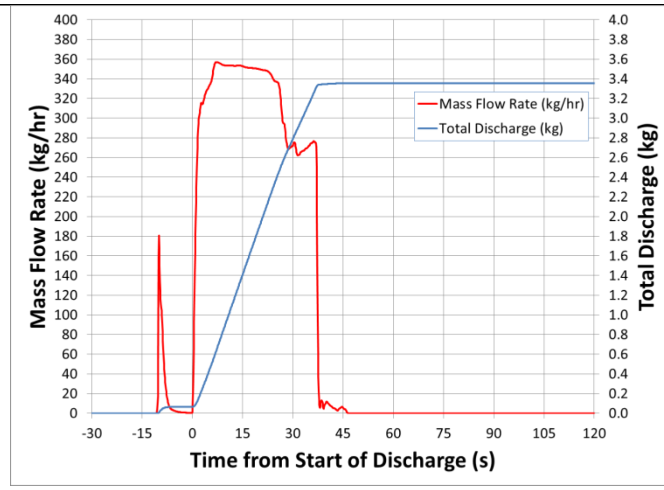
Test PA04: The parameters for the test were as follows:

Refrigerant	Temperature and Humidity	Ignition Result
R-410A	91°F / 70%RH	No Ignition

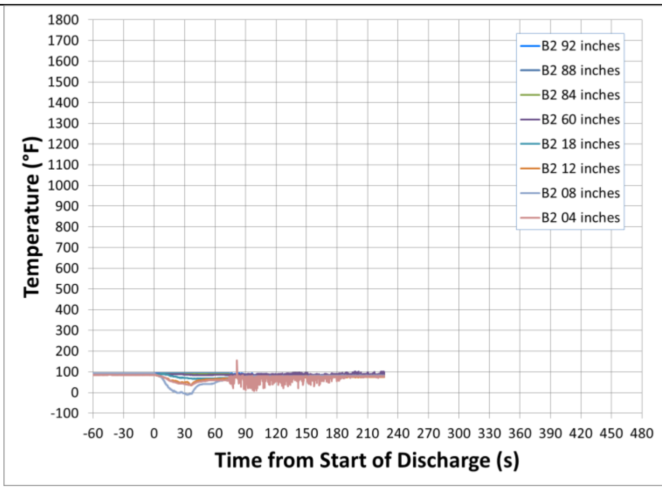
There was no ignition immediately after the electric arcs were initiated. Selected data for the test are presented in Figure 65.



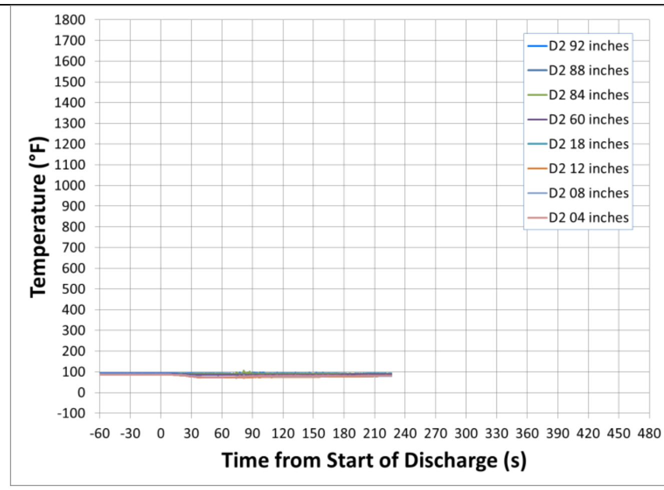
Pressure and Temperature of Release and Pressurizer Tanks



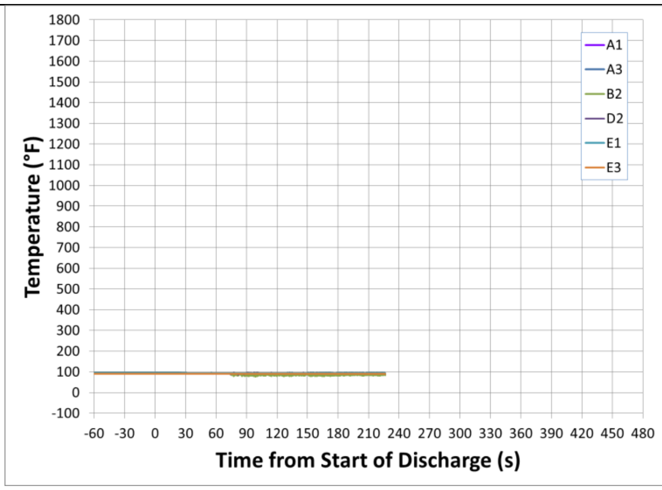
Refrigerant Release Rate



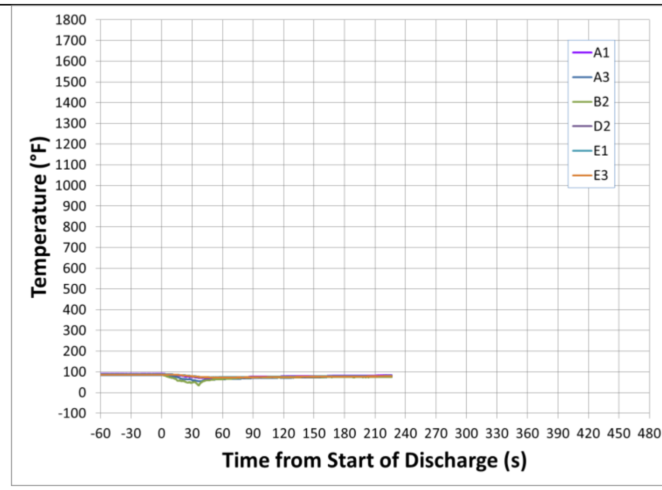
Temperature at Location B2



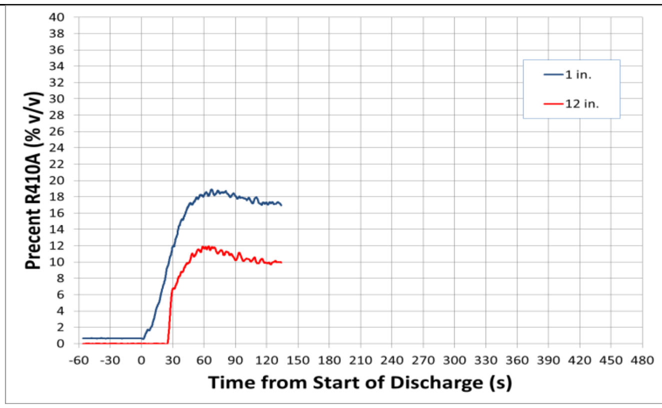
Temperature at Location D2



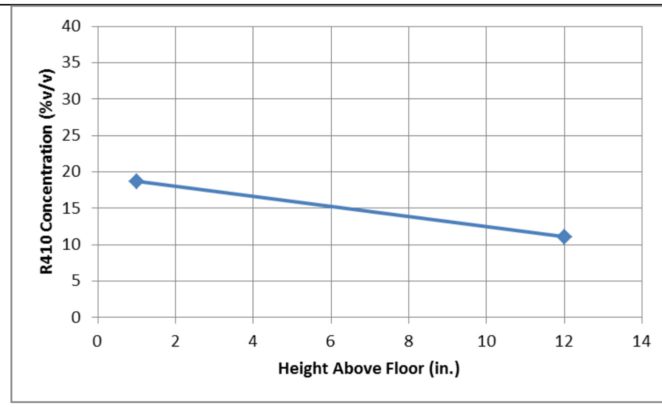
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

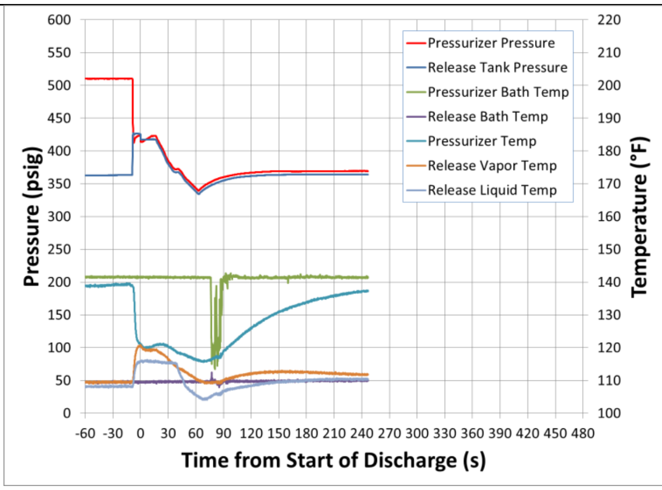
Figure 65 – Data for PA04

3.4.6.2. *Influence of Obstruction*

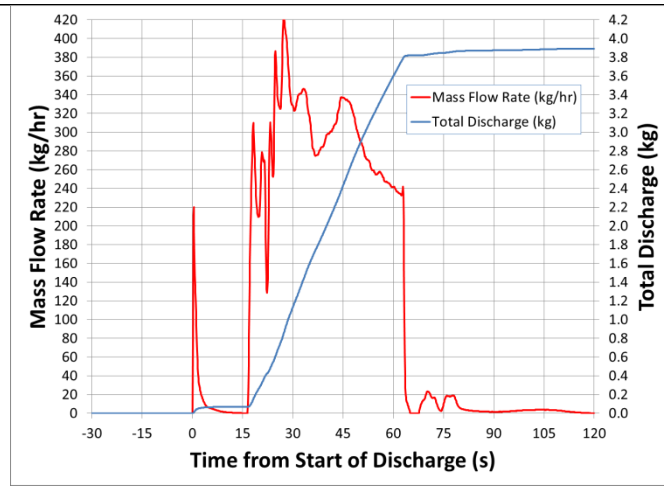
Test PB01: The parameters for the test were as follows:

Refrigerant	Obstruction	Ignition Result
R-32	Yes	Ignition

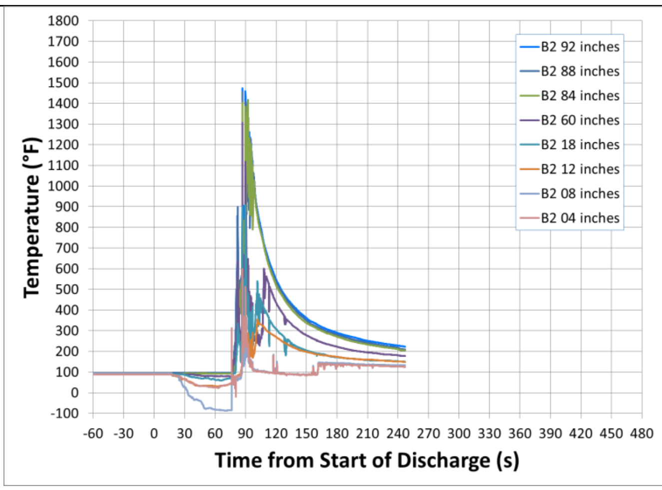
There was ignition immediately after the electric arcs were initiated, and the flaming continued for another 26s. Selected data for the test are presented in Figure 66.



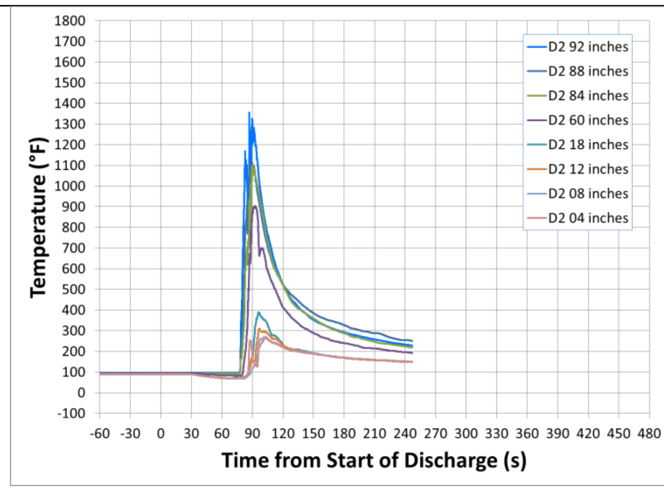
Pressure and Temperature of Release and Pressurizer Tanks



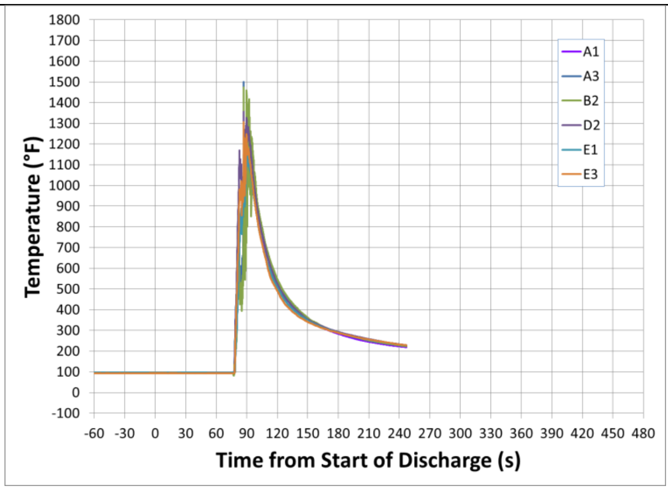
Refrigerant Release Rate



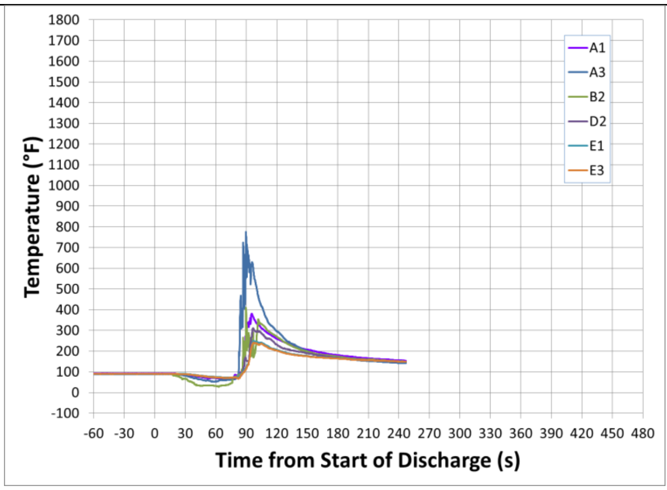
Temperature at Location B2



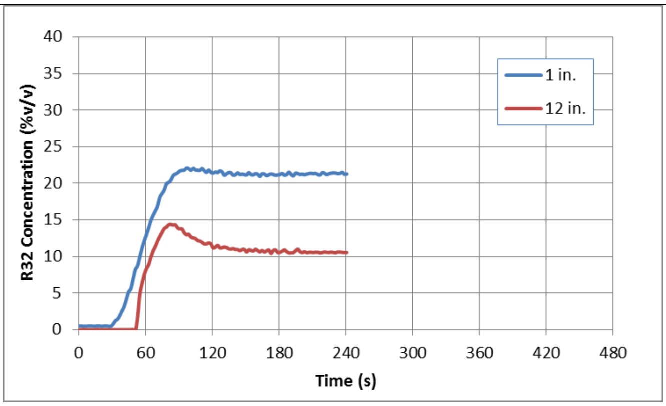
Temperature at Location D2



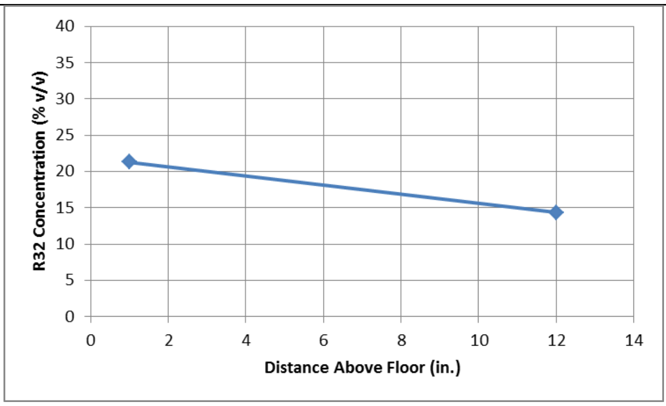
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

After End of Release with Electric arcs Energized

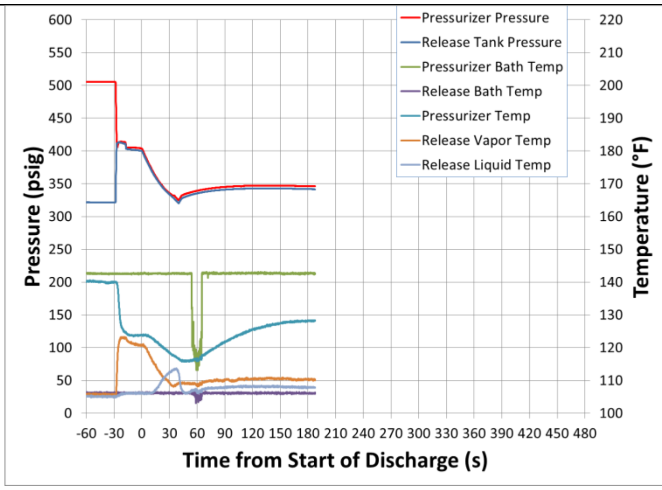
7s after Electric arcs are Energized

Figure 66 – Data for PB01

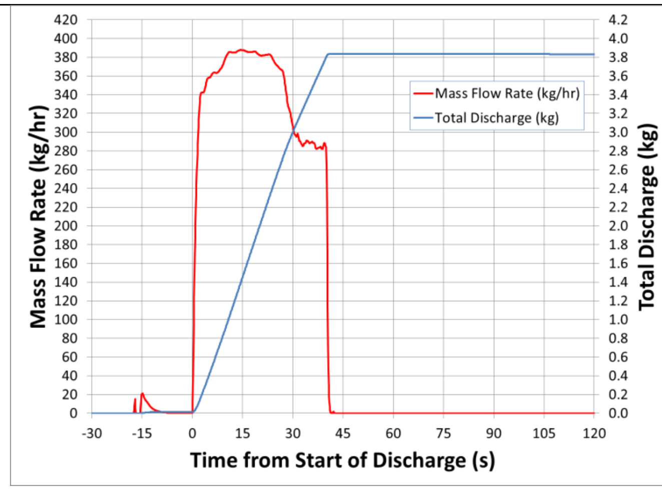
Test PB02: The parameters for the test were as follows:

Refrigerant	Obstruction	Ignition Result
R-452B	Yes	Ignition

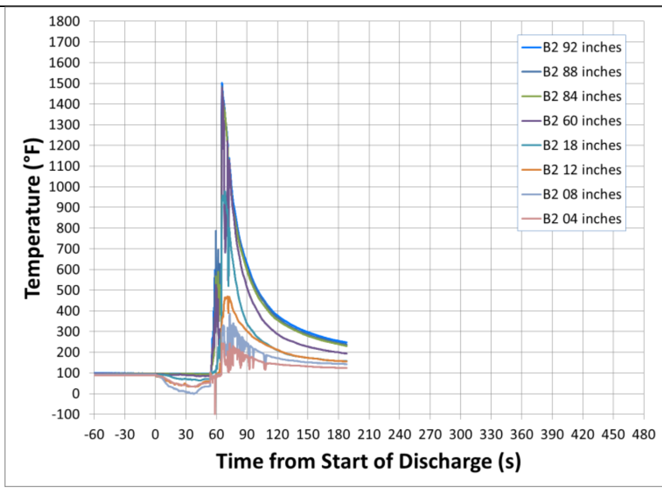
There was ignition immediately after the electric arcs were initiated, and the flaming continued for another 31s. Selected data for the test are presented in Figure 67.



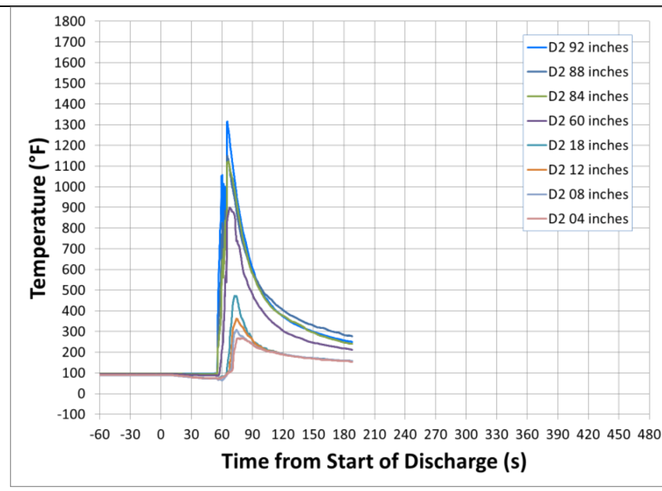
Pressure and Temperature of Release and Pressurizer Tanks



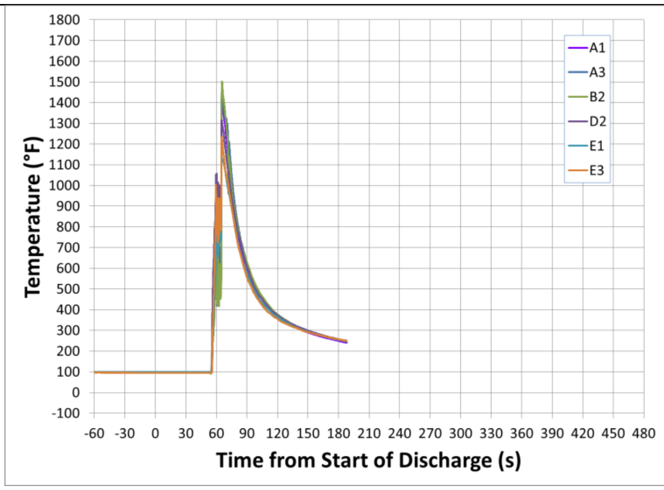
Refrigerant Release Rate



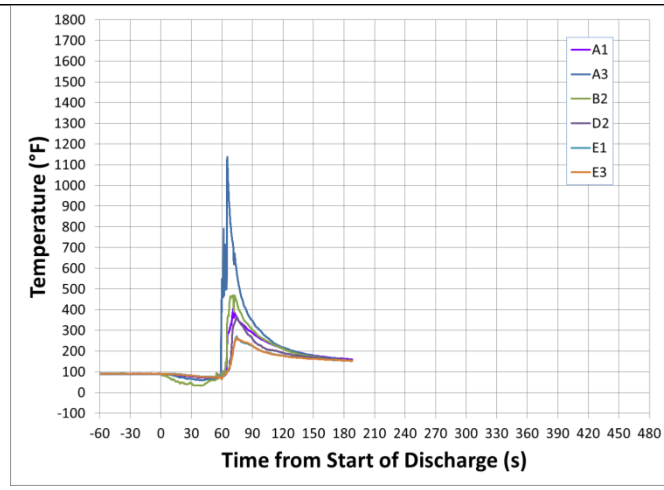
Temperature at Location B2



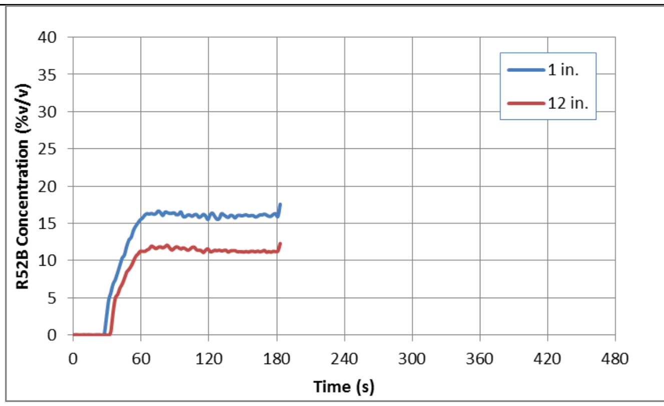
Temperature at Location D2



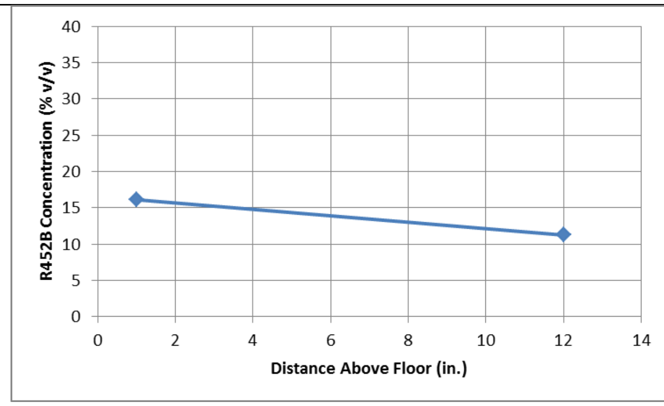
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

After End of Release with Electric arcs Energized

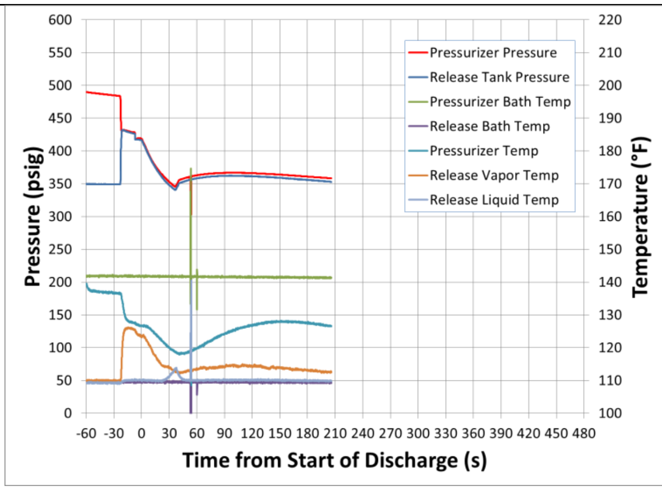
7s after Electric arcs are Energized

Figure 67 – Data for PB02

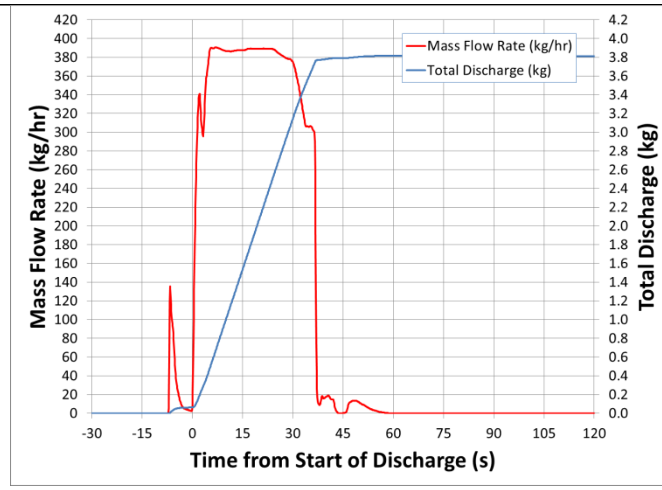
Test PB03: The parameters for the test were as follows:

Refrigerant	Obstruction	Ignition Result
R-452B	No	Ignition

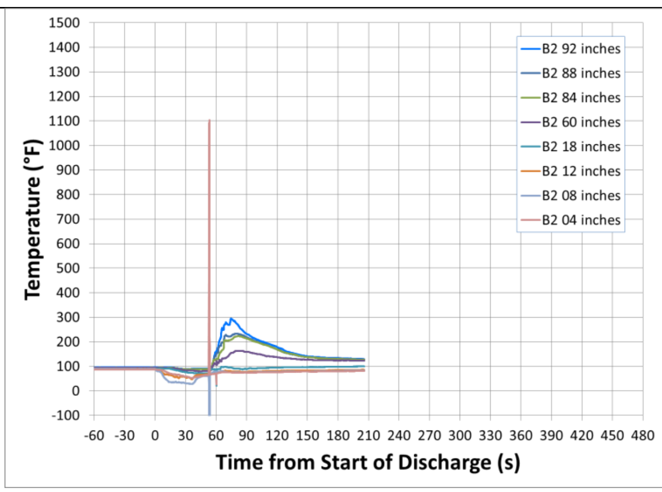
There was ignition immediately after the electric arcs were initiated, and the flaming continued for another 33s. Selected data for the test are presented in Figure 68.



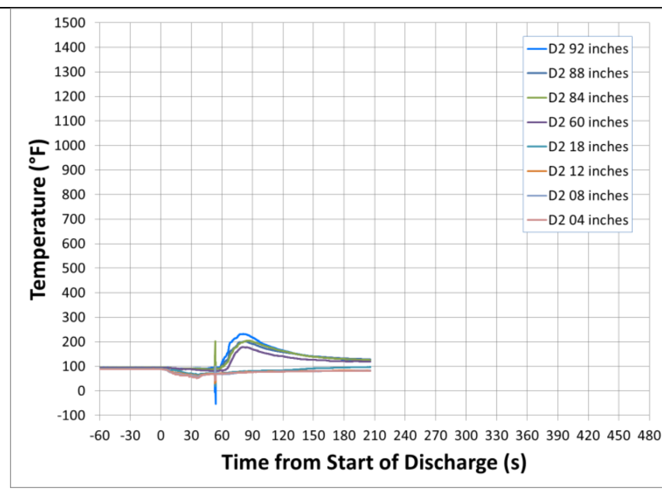
Pressure and Temperature of Release and Pressurizer Tanks



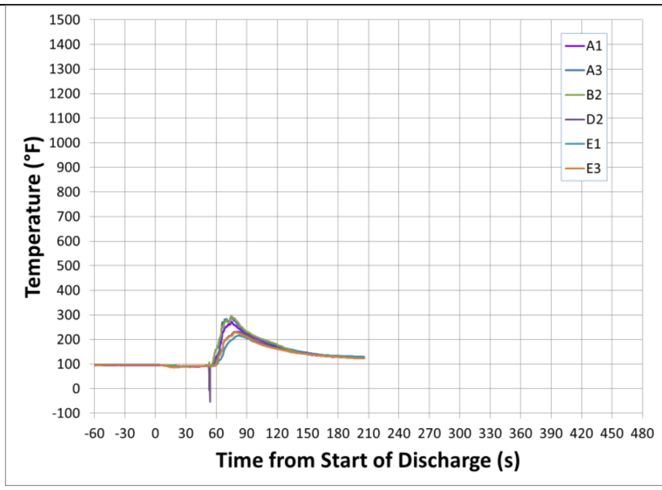
Refrigerant Release Rate



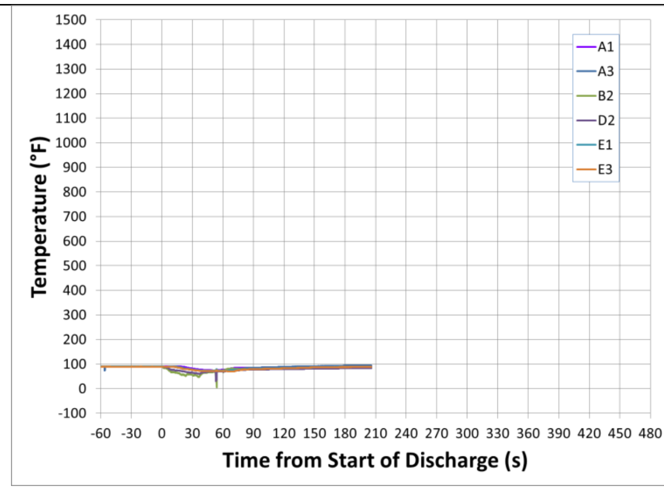
Temperature at Location B2



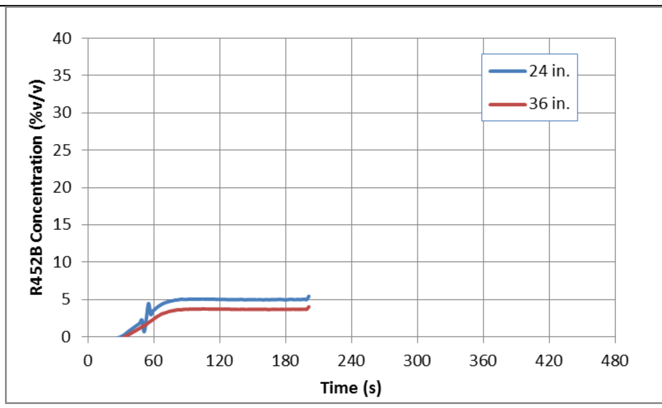
Temperature at Location D2



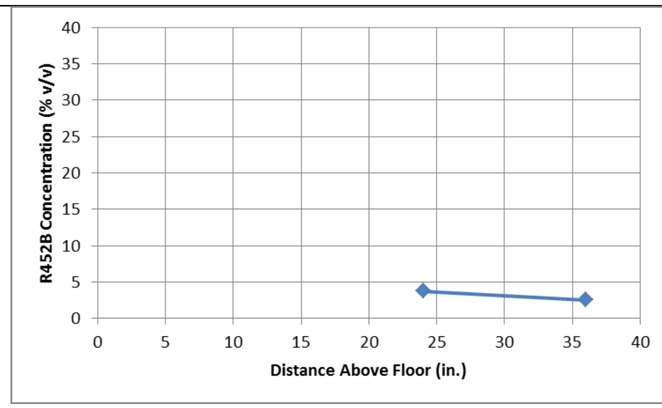
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor

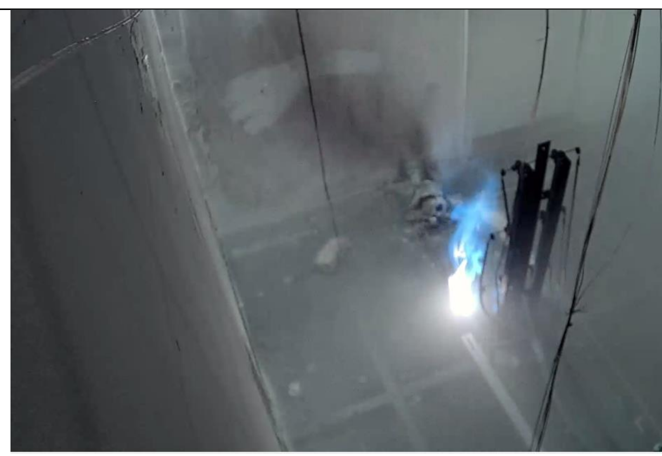


Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

After End of Release with Electric arcs Energized



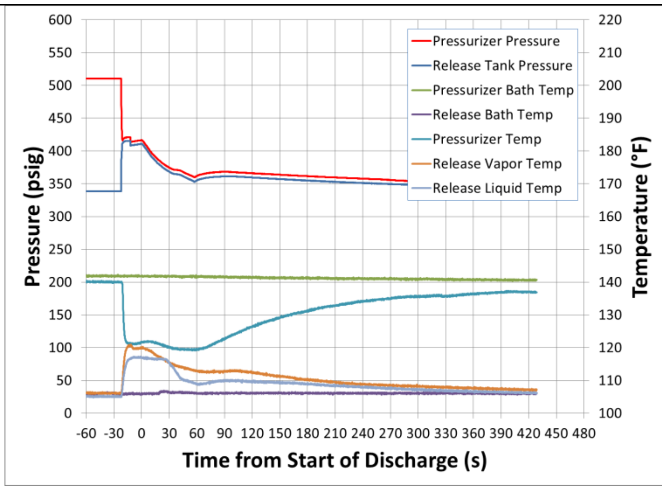
6s after Electric arcs are Energized

Figure 68 – Data for PB03

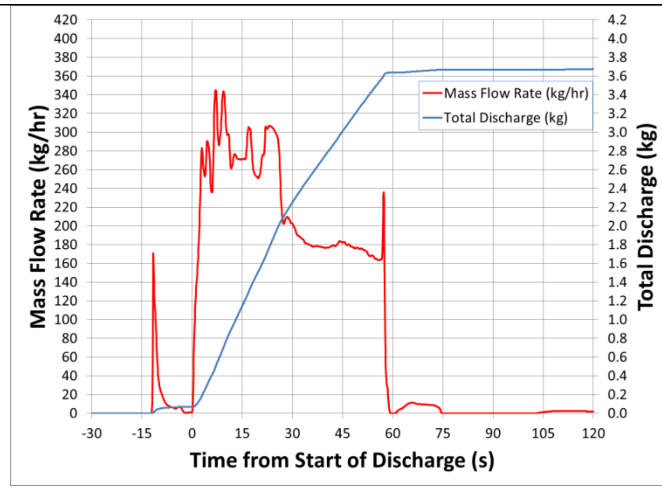
Test PB05: The parameters for the test were as follows:

Refrigerant	Obstruction	Ignition Result
R-410A	No	No Ignition

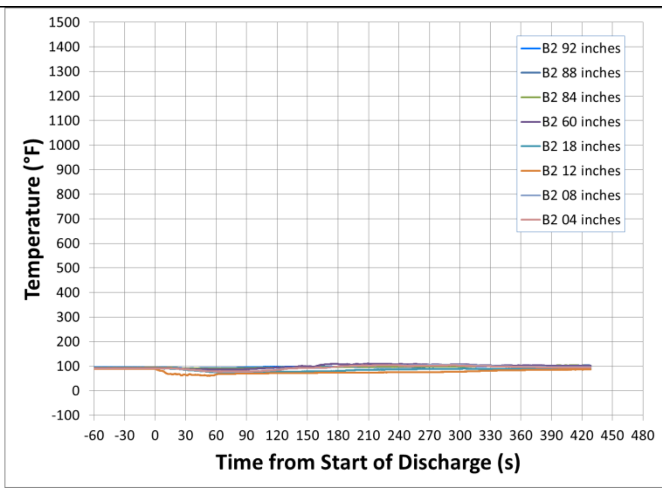
Selected data for the test are presented in Figure 69.



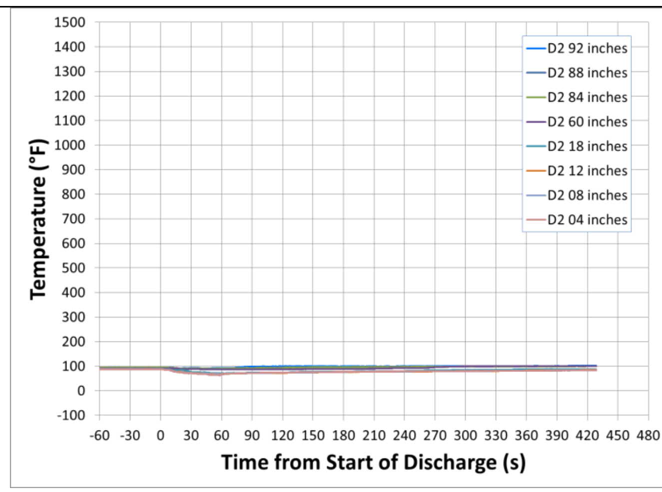
Pressure and Temperature of Release and Pressurizer Tanks



Refrigerant Release Rate



Temperature at Location B2



Temperature at Location D2

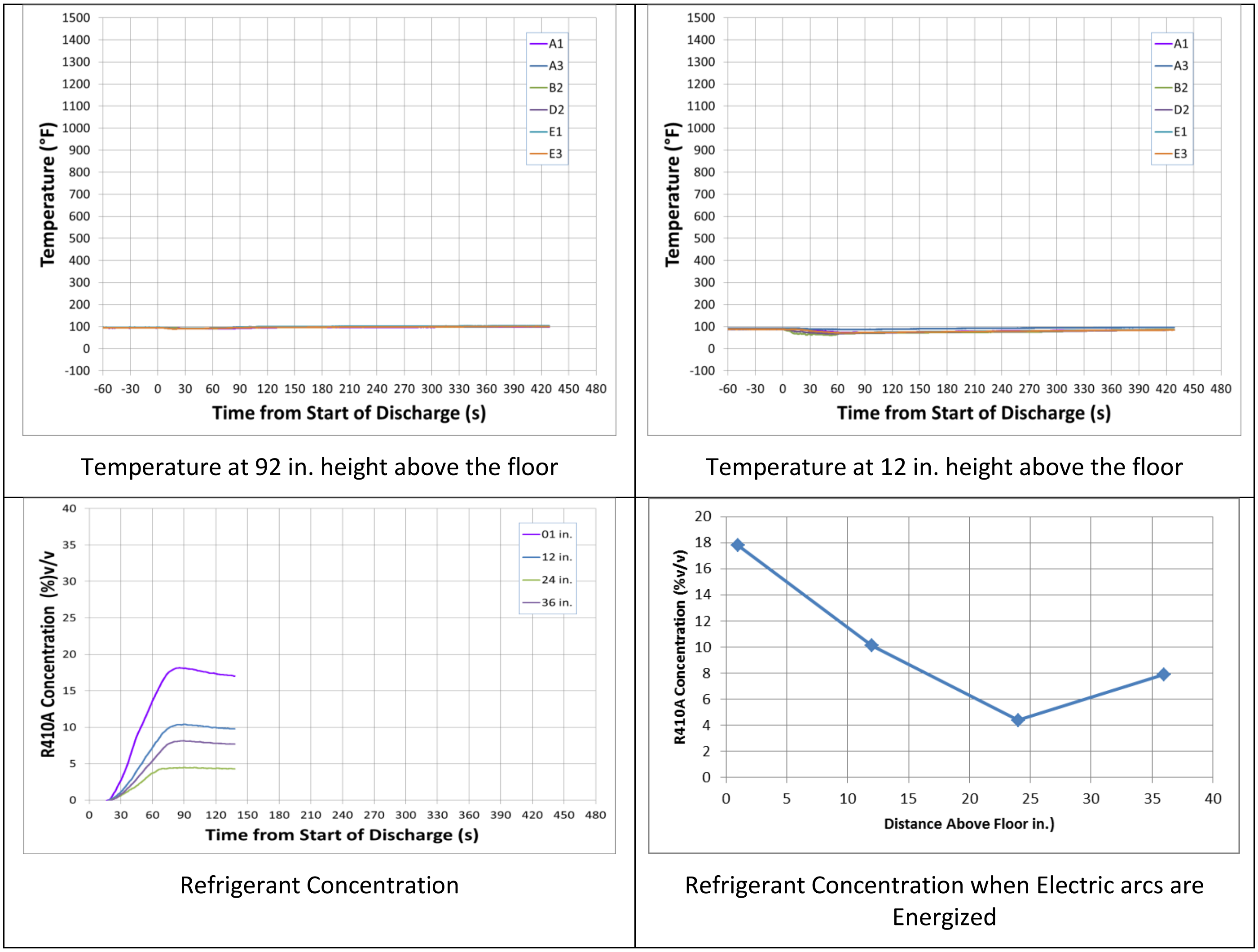
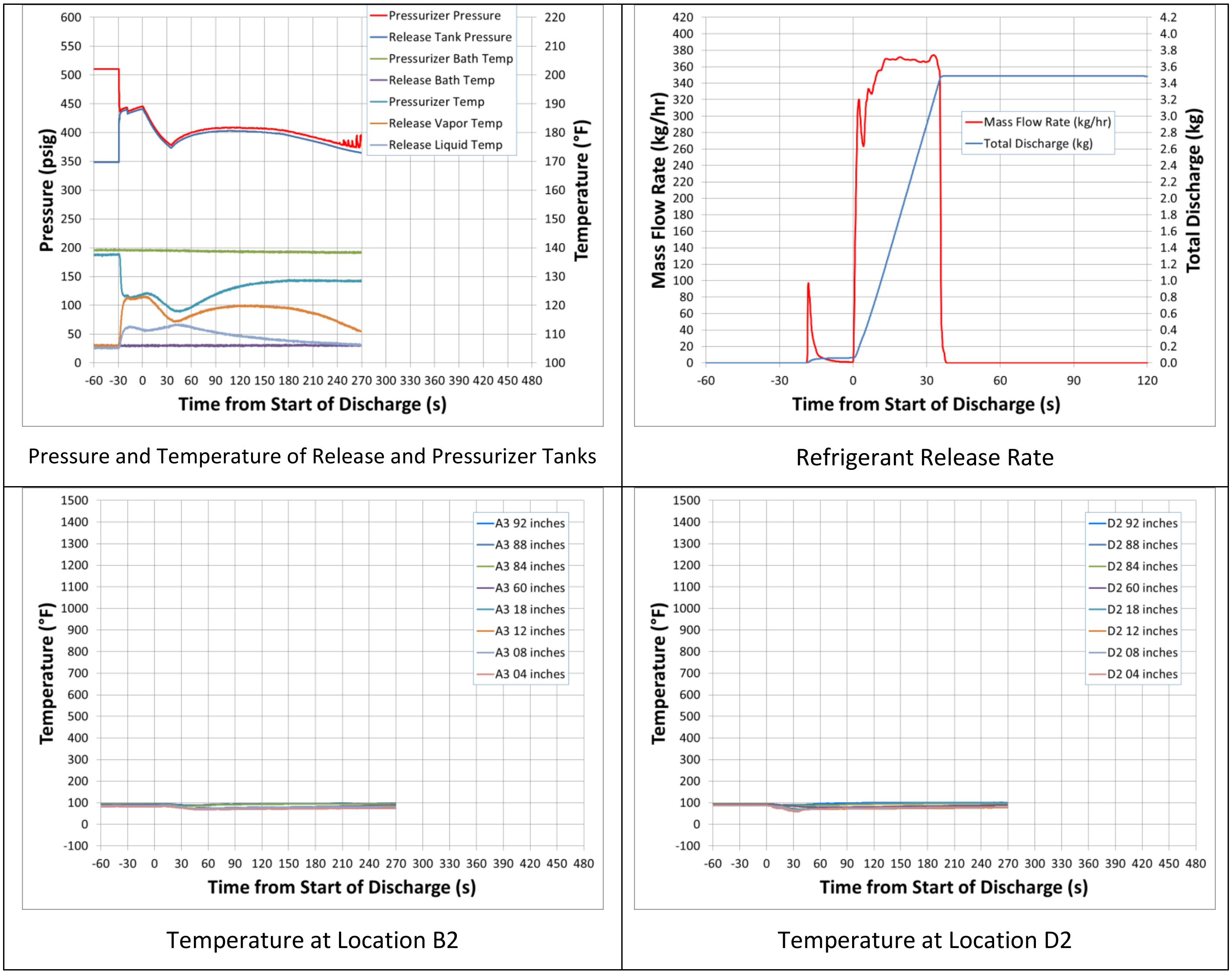


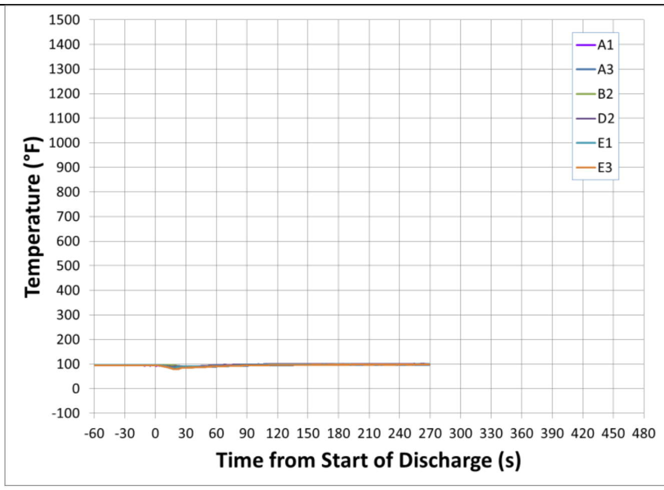
Figure 69 – Data for PB05

Test PB12: The parameters for the test were as follows:

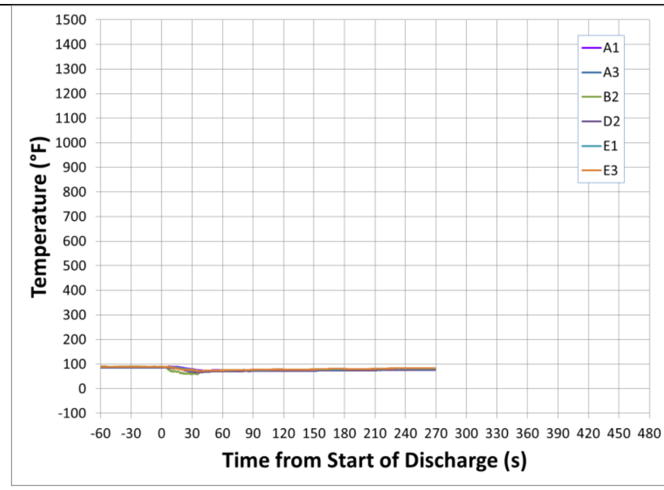
Refrigerant	Obstruction	Ignition Result
R-32	No	No Ignition

Selected data for the test are presented in Figure 70.

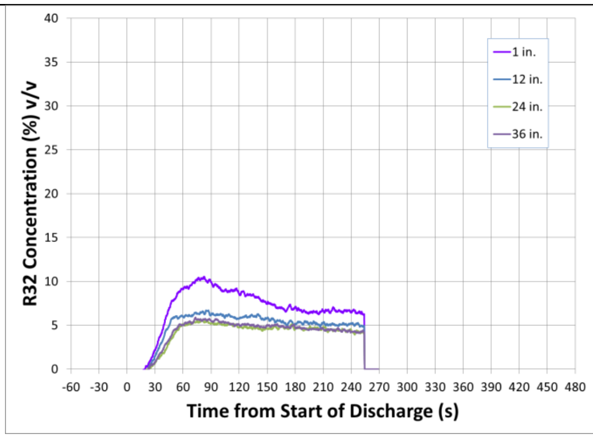




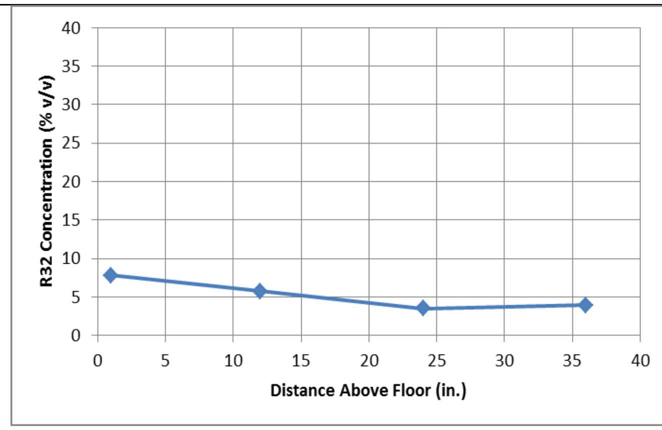
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

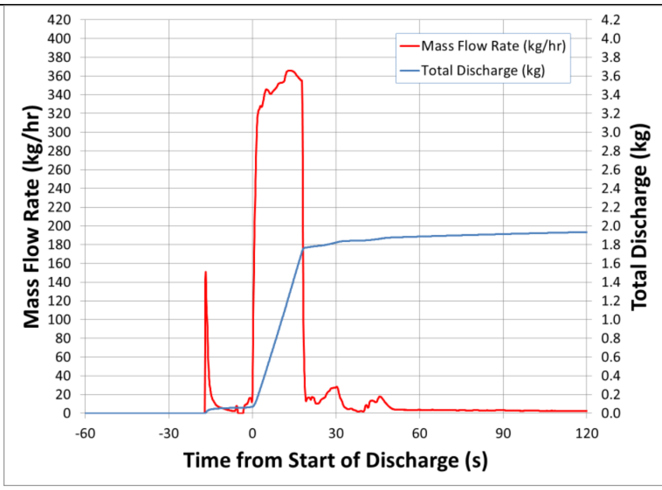
Figure 70 – Data for PB12

3.4.6.3. Influence of Refrigerant Quantity Released

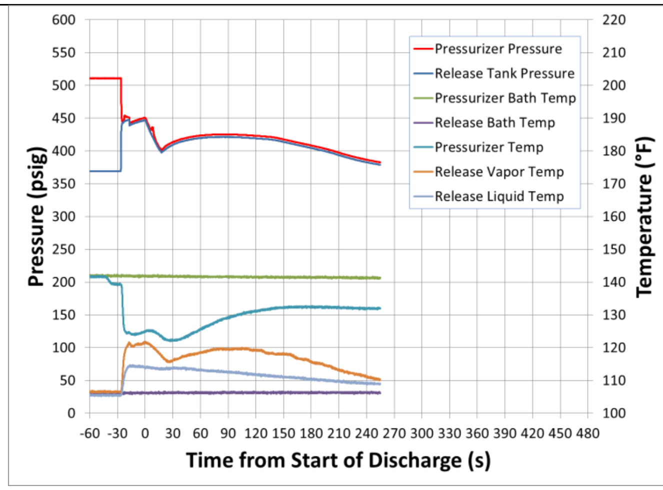
Test PB08: The parameters for the test were as follows:

Refrigerant	Refrigerant Quantity	Obstruction	Ignition Result
R-32	25% LFL	No obstruction	No Ignition

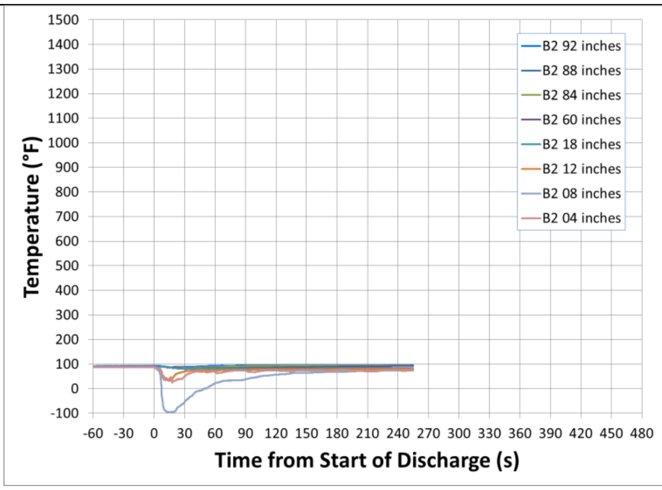
Selected data for the test are presented in Figure 71.



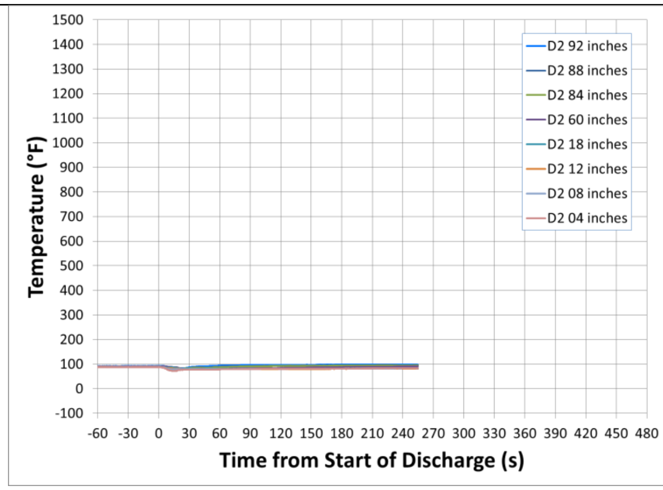
Pressure and Temperature of Release and Pressurizer Tanks



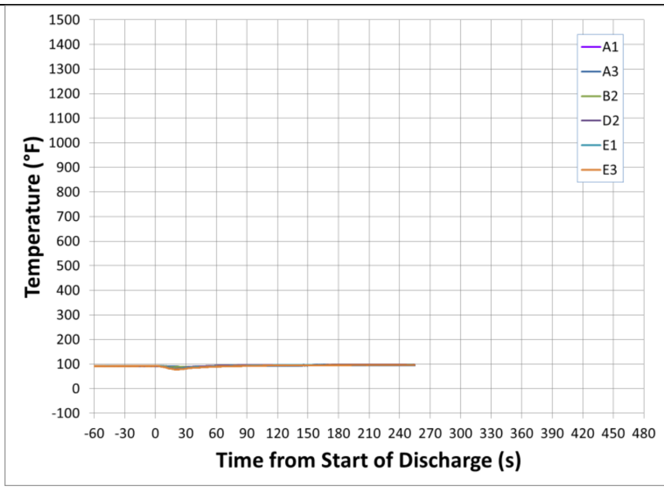
Refrigerant Release Rate



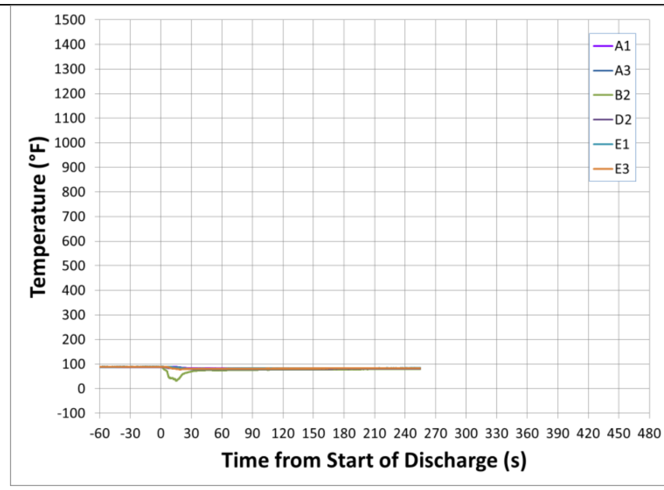
Temperature at Location B2



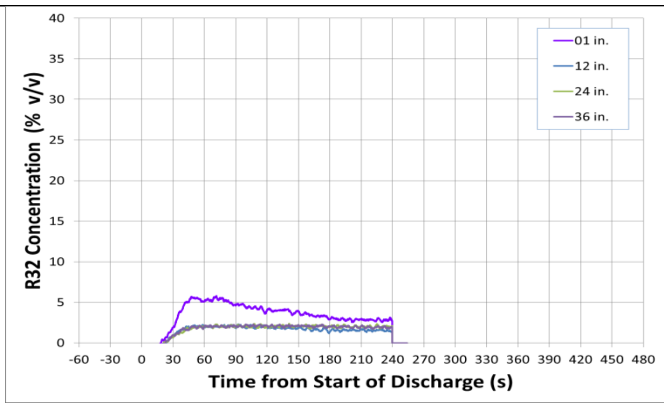
Temperature at Location D2



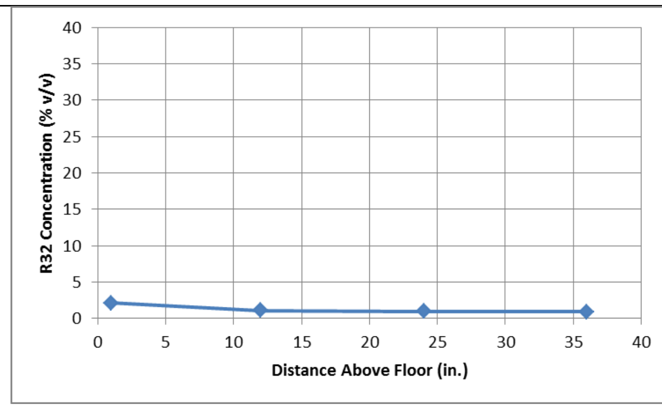
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



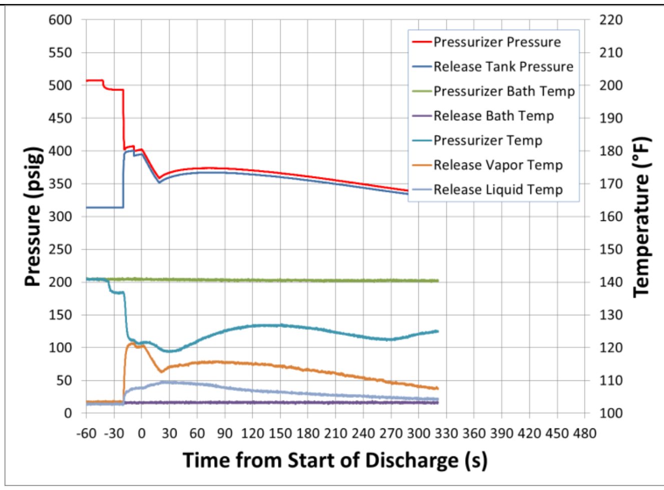
Refrigerant Concentration when Electric arcs are Energized

Figure 71 – Data for PB08

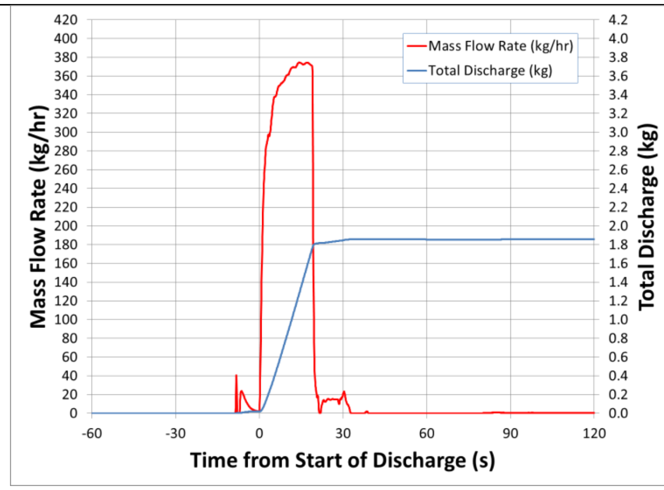
Test PB09: The parameters for the test were as follows:

Refrigerant	Refrigerant Quantity	Obstruction	Ignition Result
R-452B	25% LFL	No obstruction	No Ignition

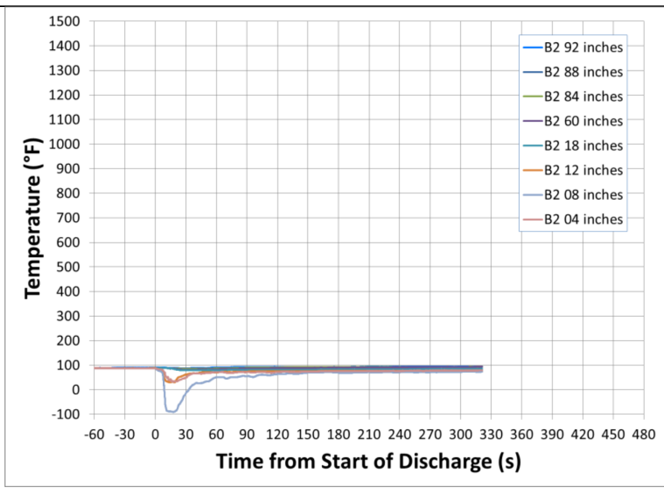
Selected data for the test are presented in Figure 72.



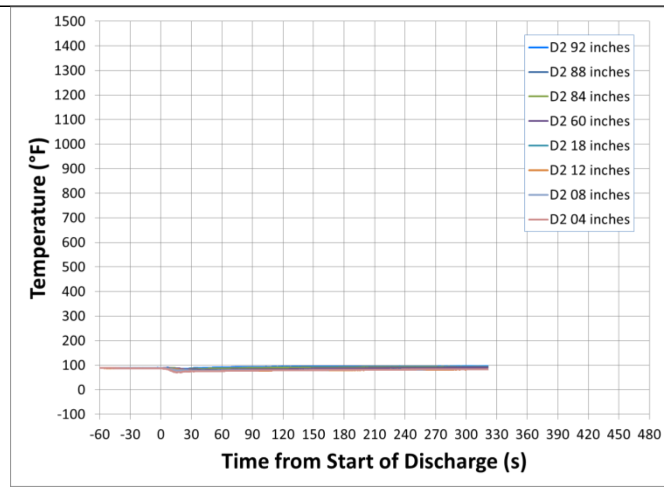
Pressure and Temperature of Release and Pressurizer Tanks



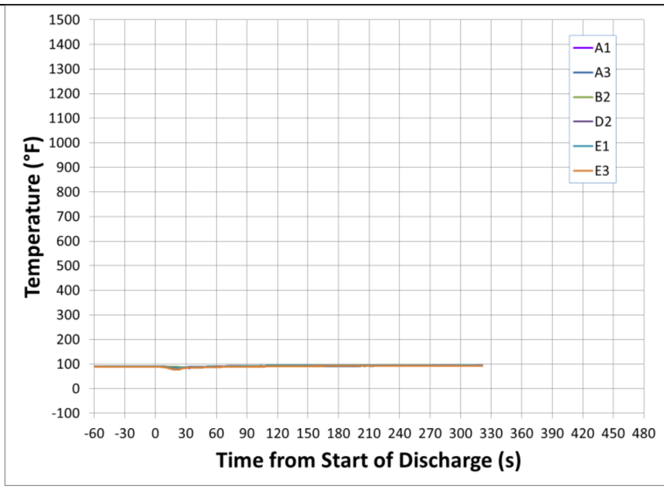
Refrigerant Release Rate



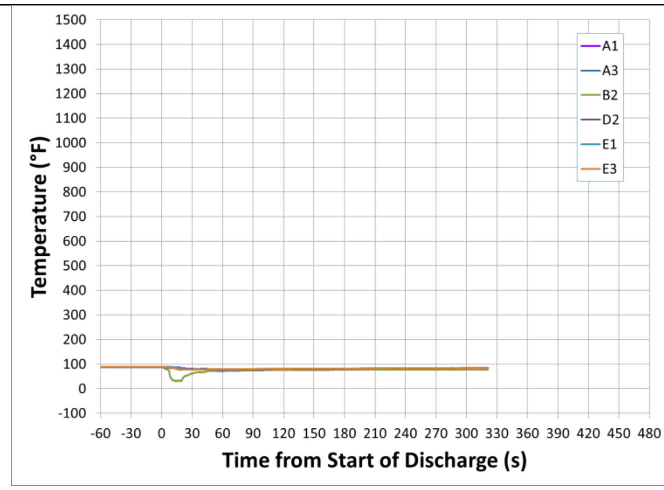
Temperature at Location B2



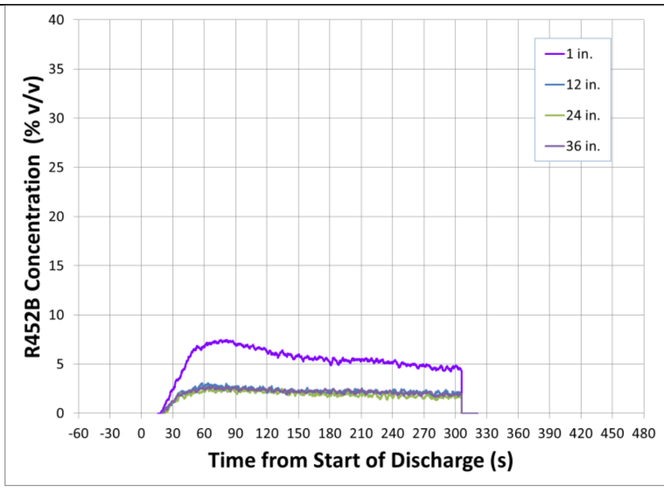
Temperature at Location D2



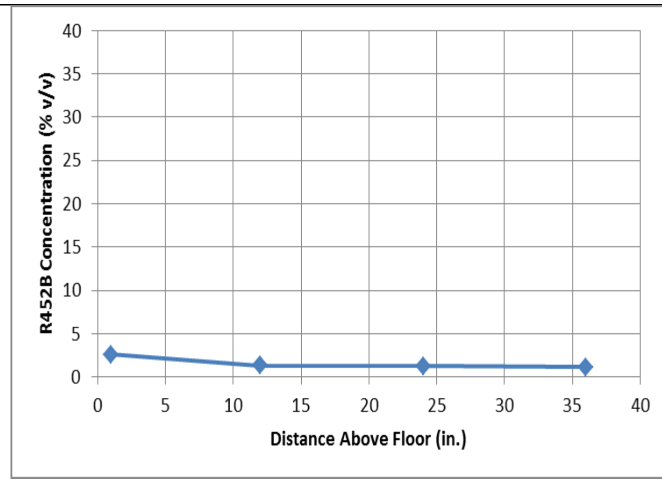
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



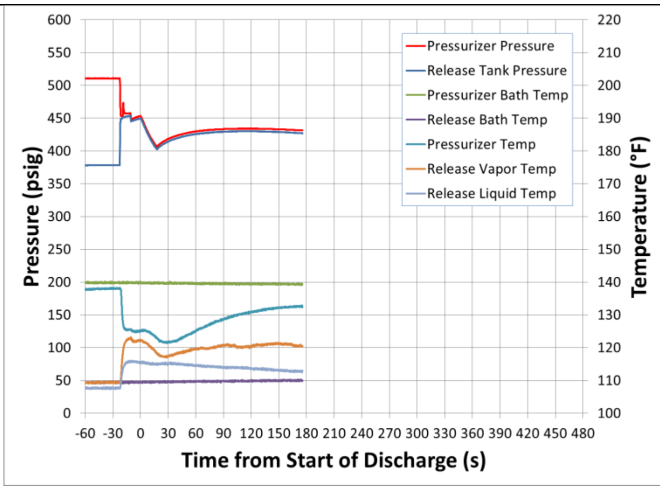
Refrigerant Concentration when Electric arcs are Energized

Figure 72 – Data for PB09

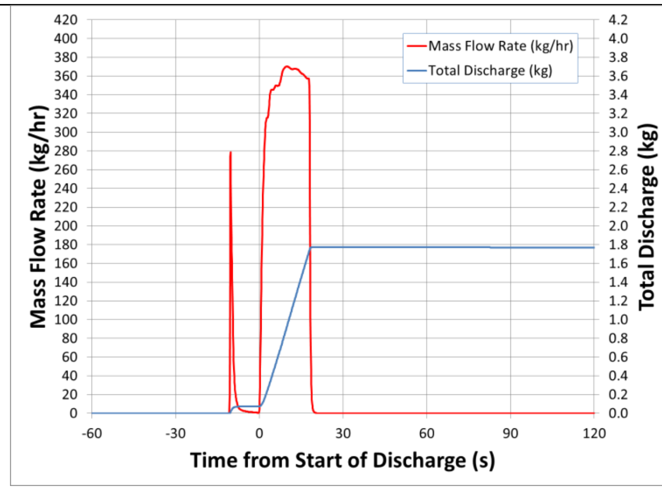
Test PB10: The parameters for the test were as follows:

Refrigerant	Refrigerant Quantity	Obstruction	Ignition Result
R-32	25% LFL	Obstruction	Ignition

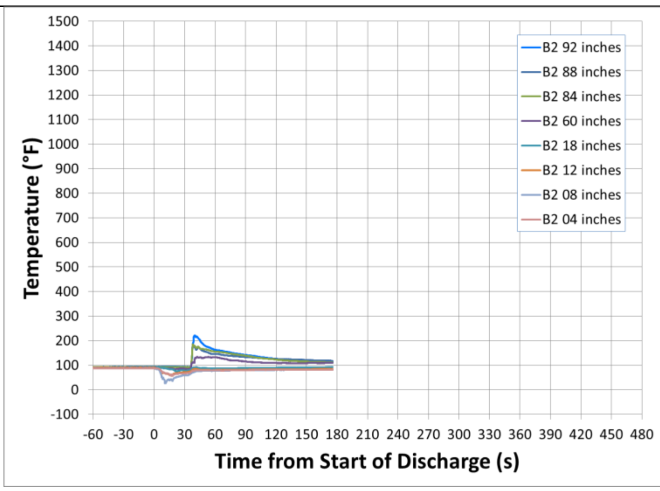
The mixture ignited after electric arcs were energized. The flaming continued for 22s. Selected data for the test are presented in Figure 73. The refrigerant sensors (deconvoluted data) did not show concentrations above the LFL. The videos show that flames did not come near the refrigerant sensors indicating that the volume of gas mixture above the LFL was concentrated near the centerline of the test room.



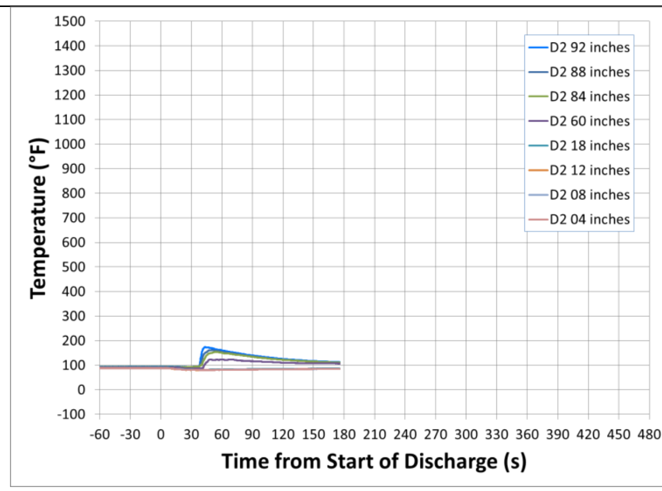
Pressure and Temperature of Release and Pressurizer Tanks



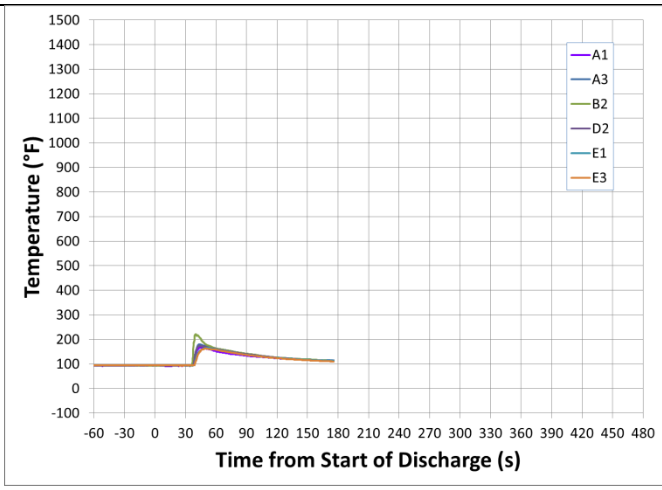
Refrigerant Release Rate



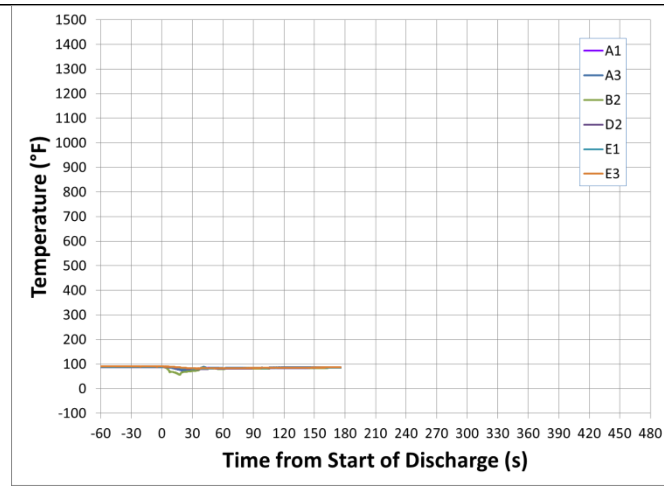
Temperature at Location B2



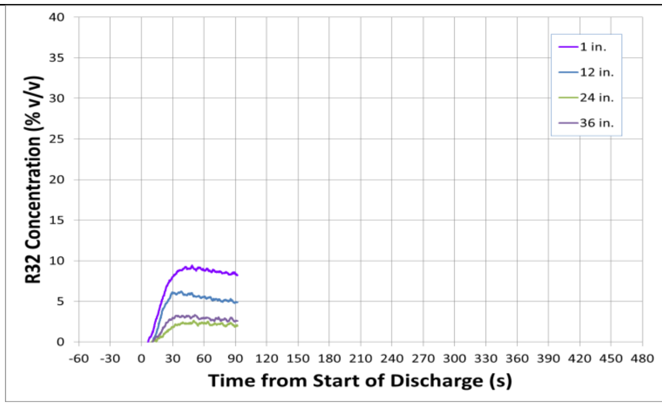
Temperature at Location D2



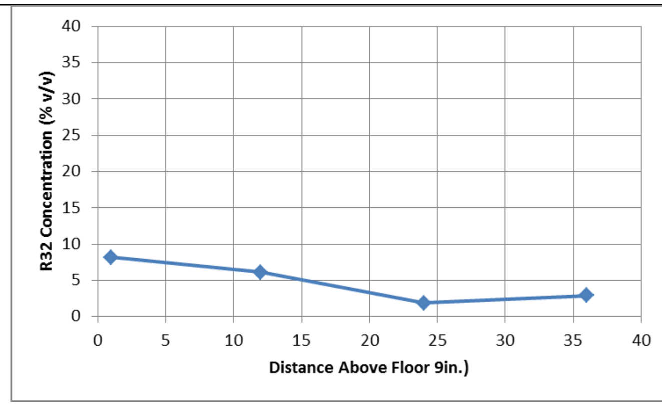
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

End of release, Electric arcs Energized

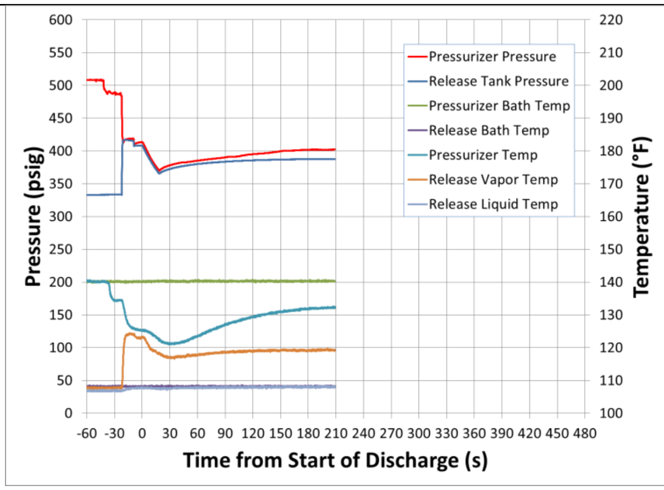
5s after Electric arcs were Energized

Figure 73 – Data for PB10

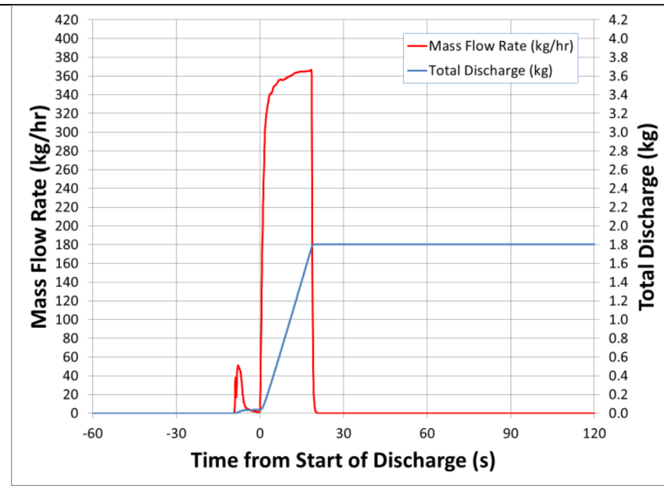
Test PB11: The parameters for the test were as follows:

Refrigerant	Refrigerant Quantity	Obstruction	Ignition Result
R-452B	25% LFL	Obstruction	Ignition

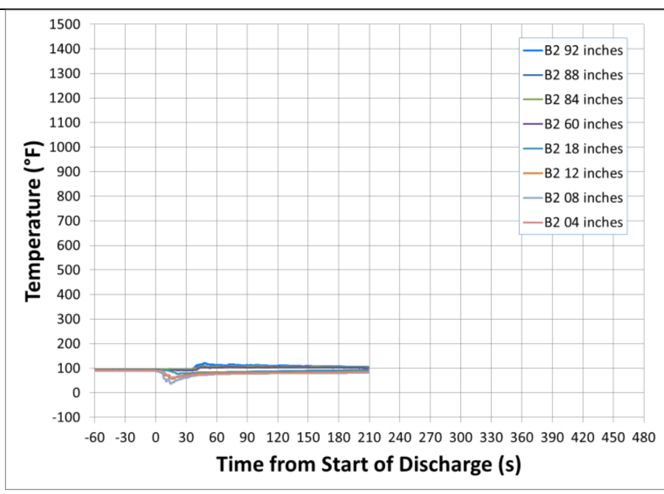
The mixture ignited 2 s after electric arcs were energized at the end of release. The flames appeared to be localized in the region of the electric arcs and the flaming continued for 18 s. The electric arcs were reenergized again 206 s after end of release without any ignition. Selected data for the test are presented in Figure 74. The refrigerant sensors (deconvoluted data) did not show concentrations above the LFL. The videos show that flames did not come near the refrigerant sensors indicating that the volume of gas mixture above the LFL was concentrated near the centerline of the test room.



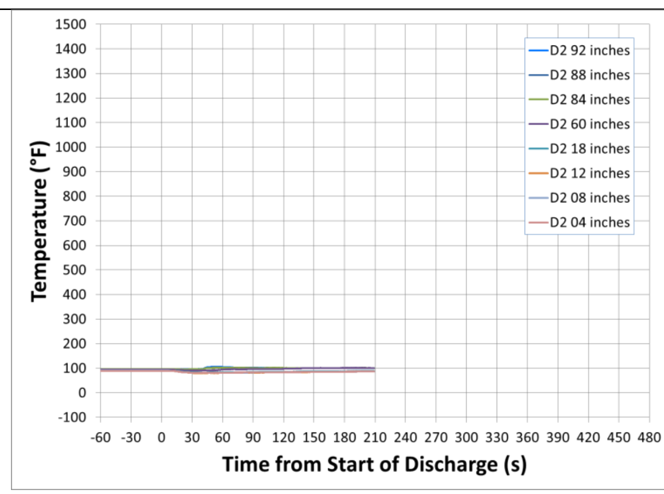
Pressure and Temperature of Release and Pressurizer Tanks



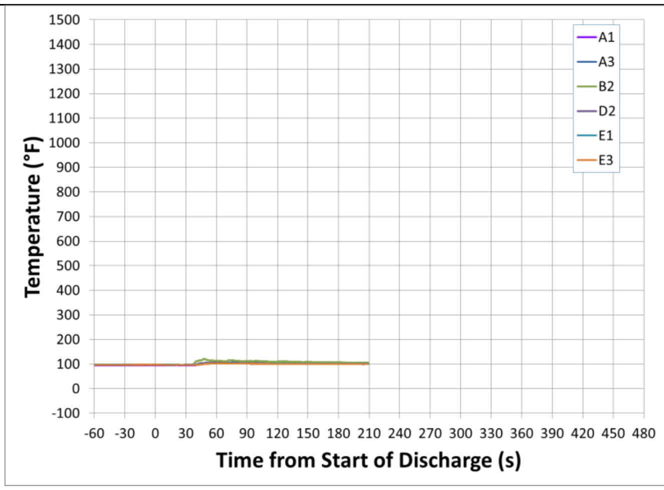
Refrigerant Release Rate



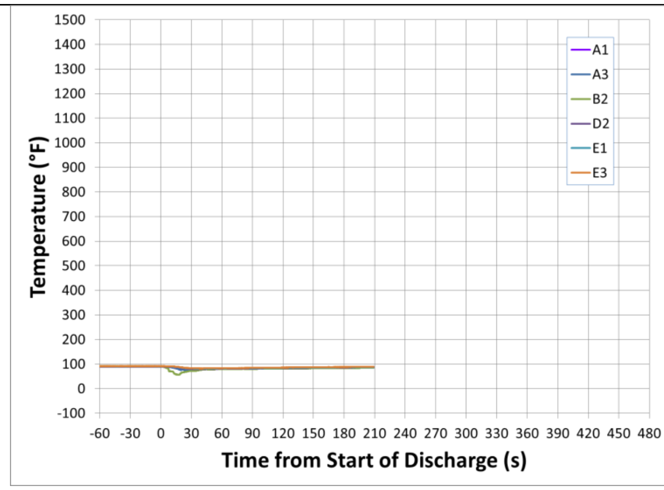
Temperature at Location B2



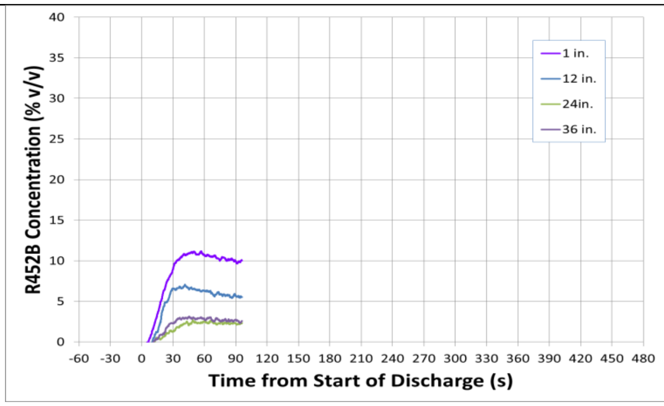
Temperature at Location D2



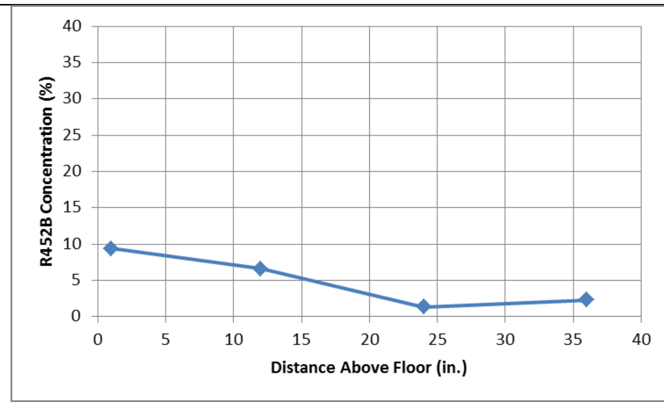
Temperature at 92 in. height above the floor



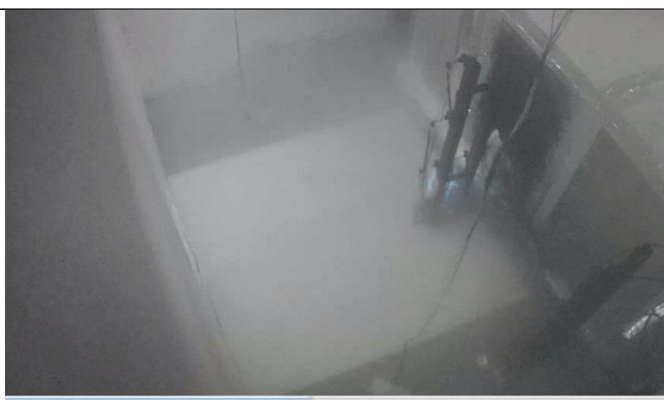
Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized



4s after Electric arcs were Energized

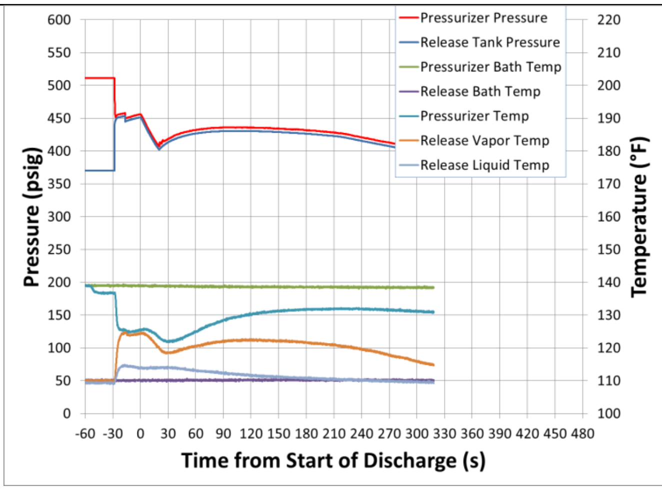
5s after Electric arced were Energized

Figure 74 – Data for PB11

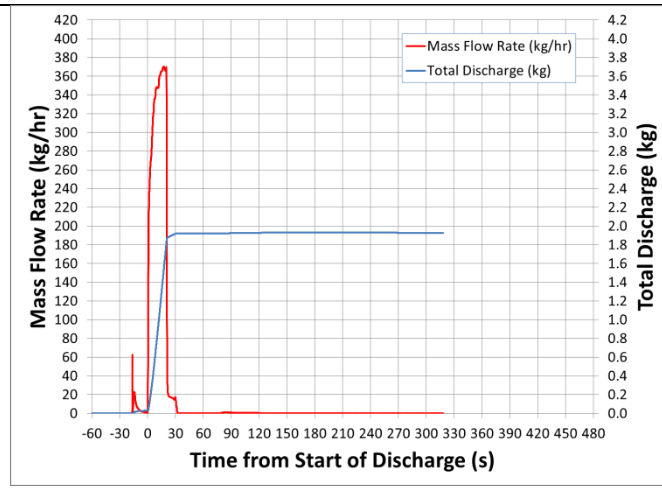
Test Cal20: The parameters for the test were as follows:

Refrigerant	Refrigerant Quantity	Obstruction	Ignition Result
R-32	25% LFL	Obstruction	No Ignition

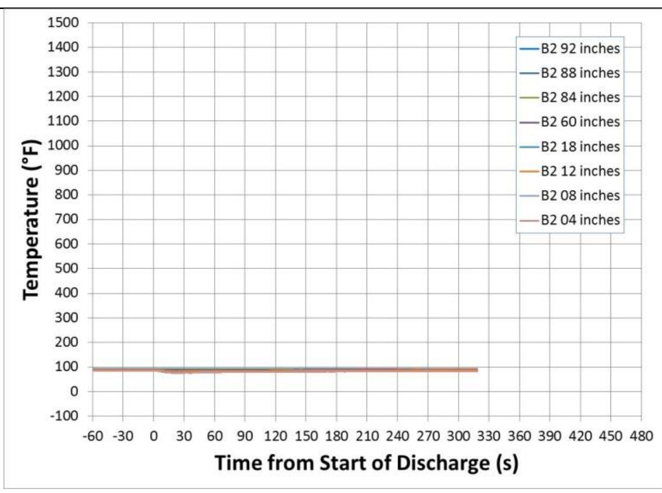
Cal20 was performed at the request of the AHRTI team. The 356 mm duct section was placed at the 2.2 m height and the release rate was 100 g/s. There was no ignition after electric arcs were energized at the end of release. Selected data for the test are presented in Figure 75.



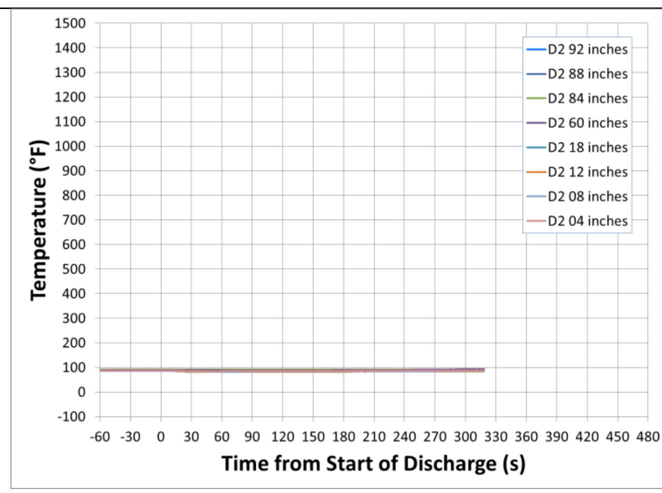
Pressure and Temperature of Release and Pressurizer Tanks



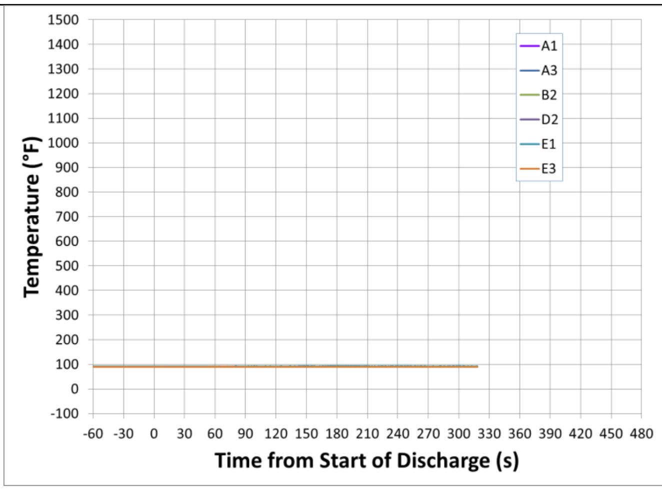
Refrigerant Release Rate



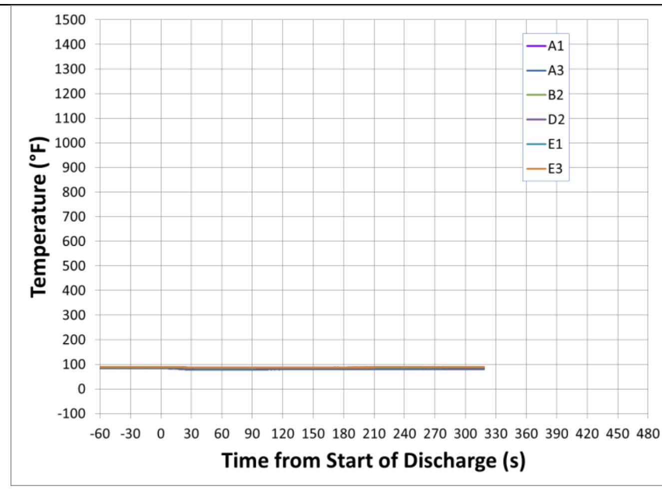
Temperature at Location B2



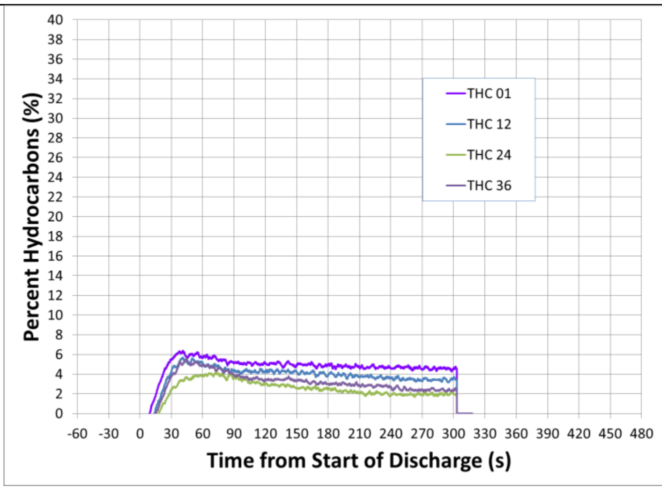
Temperature at Location D2



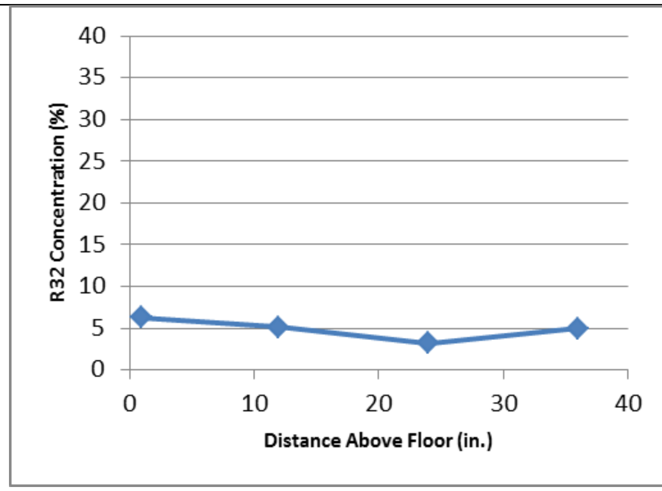
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

Figure 75 – Data for Cal20

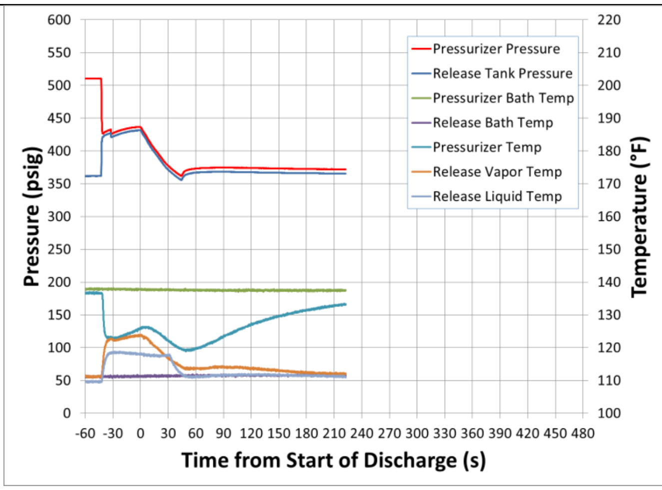
3.4.6.4. Influence of Lubricating Oil

The results from each of the tests are presented herein.

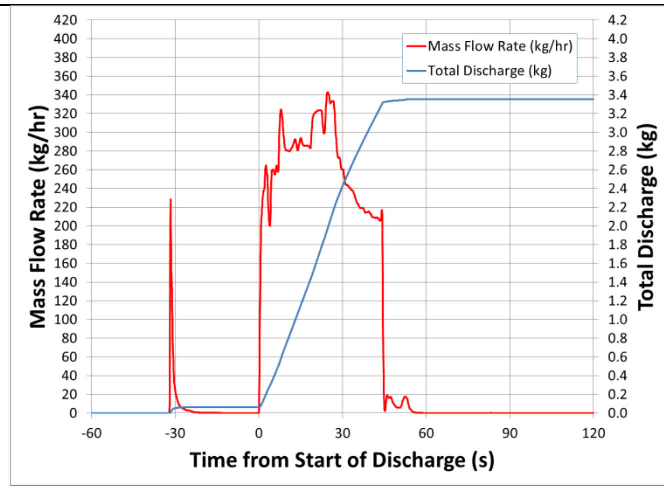
Test PC07: The parameters for the test were as follows:

Refrigerant	Oil Concentration	Ignition Result
R-410A	1.5%	No Ignition

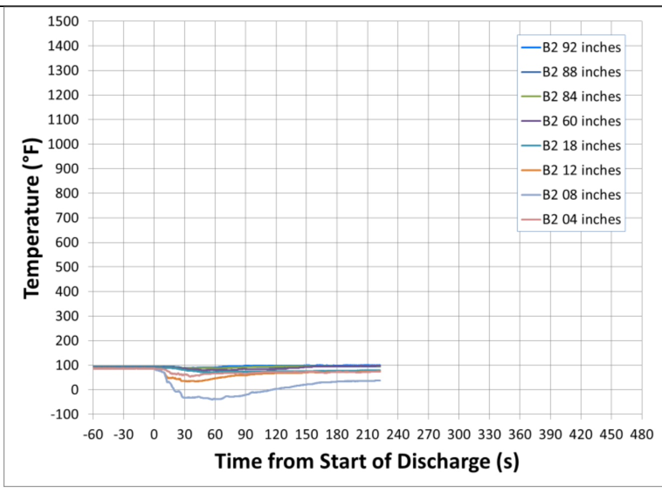
The refrigerant and oil mixture did not ignite. Selected data for the test are presented in Figure 76.



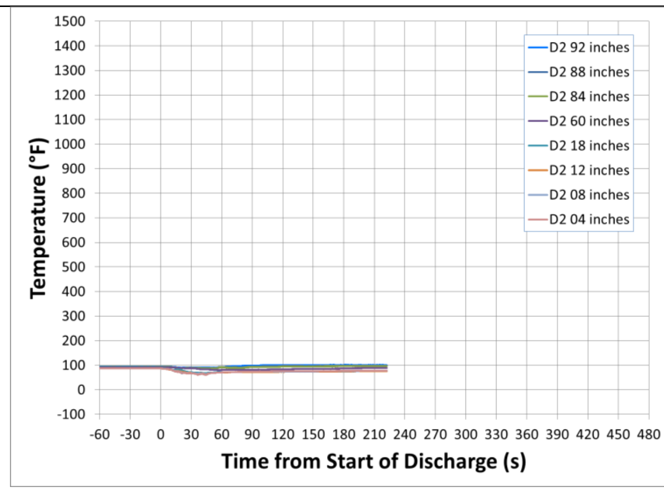
Pressure and Temperature of Release and Pressurizer Tanks



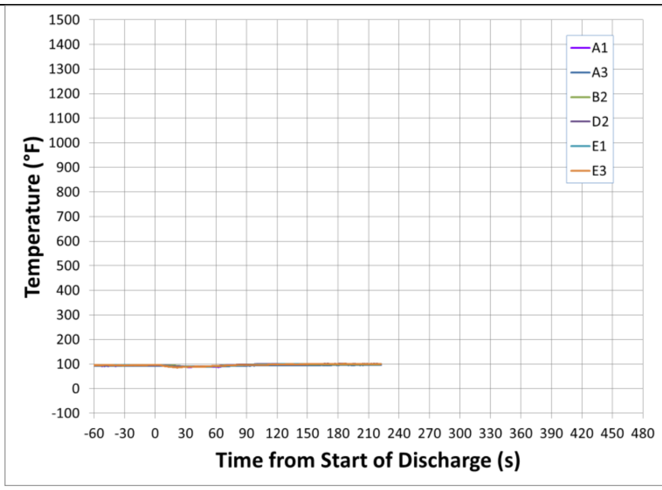
Refrigerant Release Rate



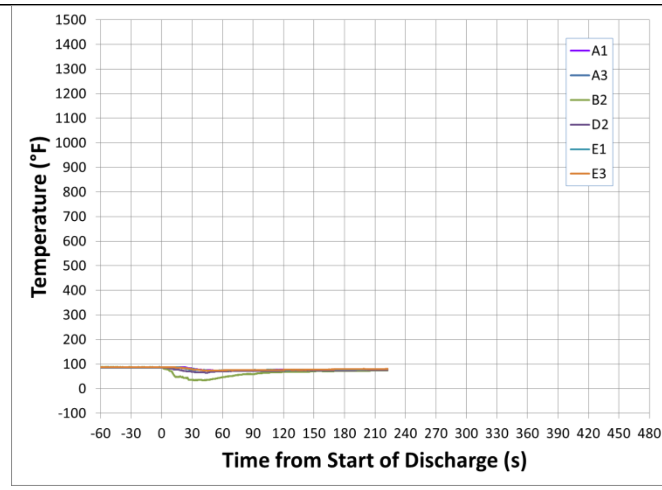
Temperature at Location B2



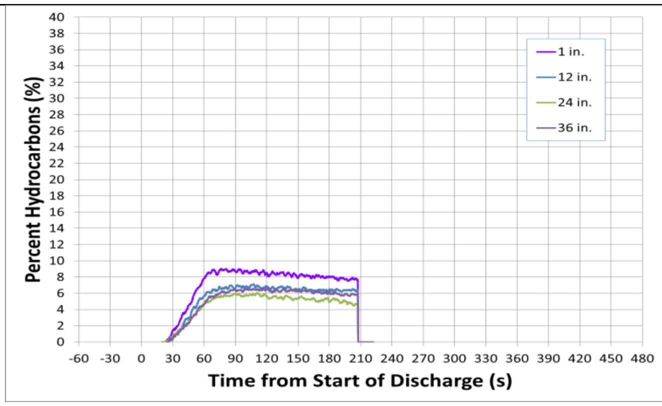
Temperature at Location D2



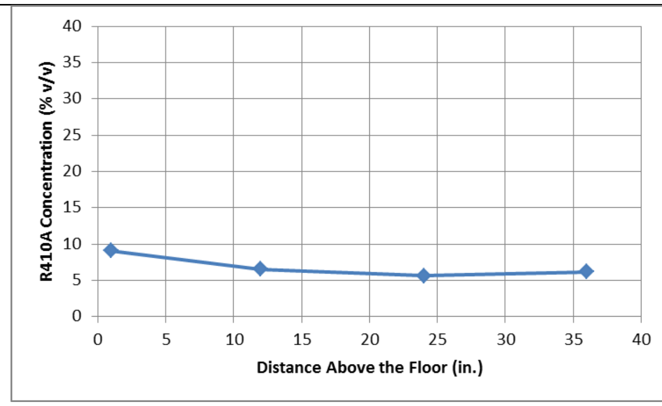
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



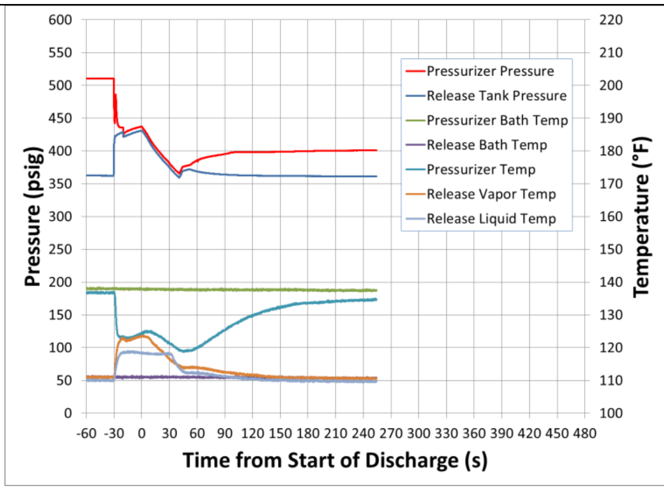
Refrigerant Concentration when Electric arcs are Energized

Figure 76 – Data for PC07

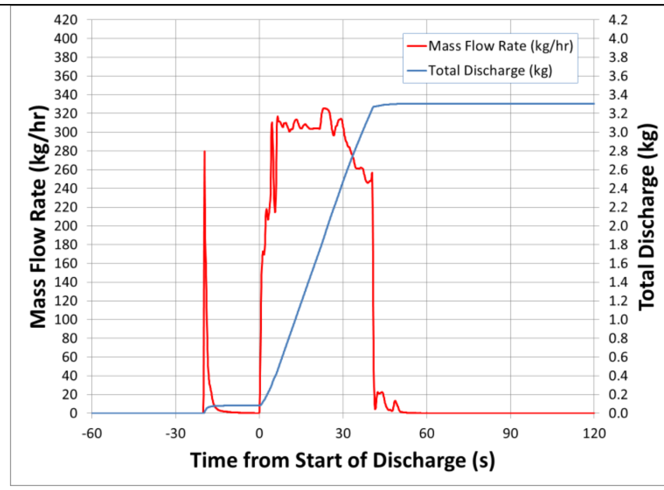
Test PC08: The parameters for the test were as follows:

Refrigerant	Oil Concentration	Ignition Result
R-410A	3.0%	No Ignition

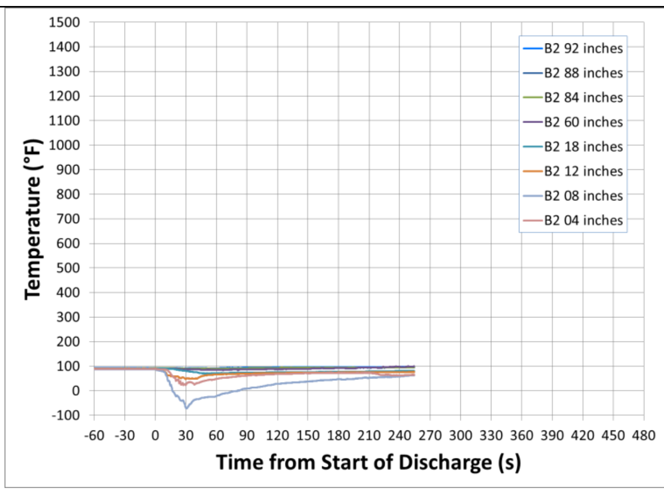
The refrigerant and oil mixture did not ignite. Selected data for the test are presented in Figure 77.



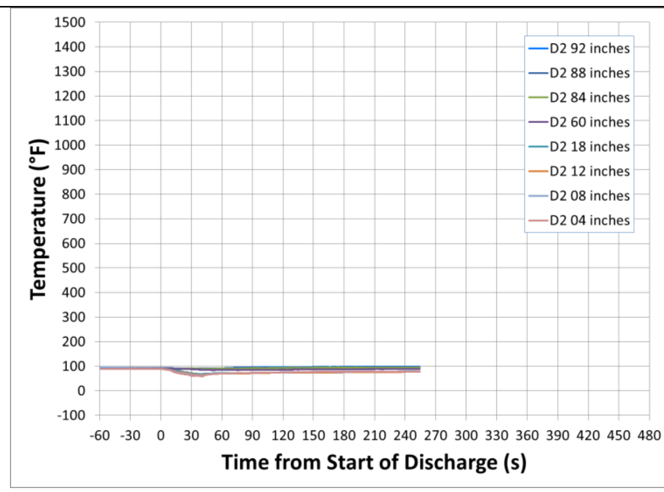
Pressure and Temperature of Release and Pressurizer Tanks



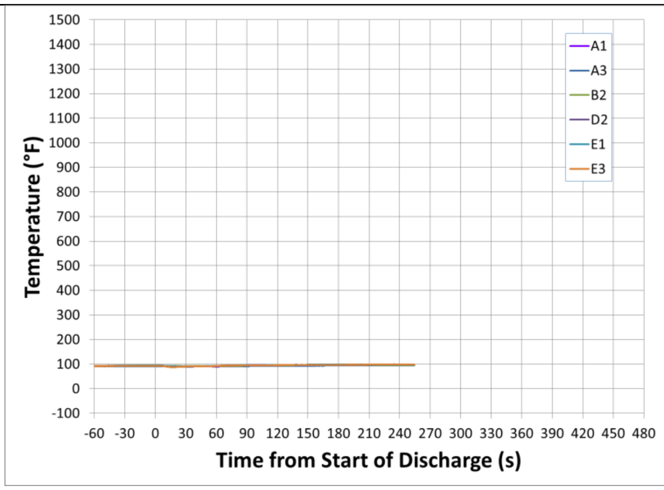
Refrigerant Release Rate



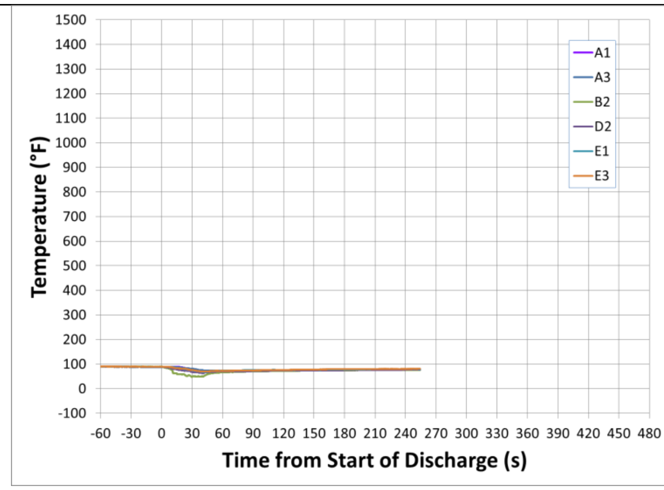
Temperature at Location B2



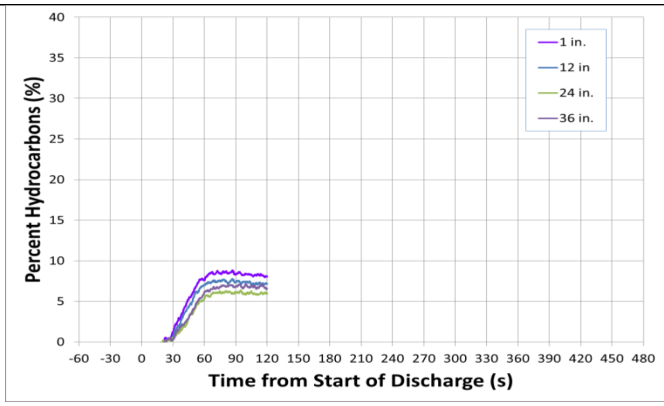
Temperature at Location D2



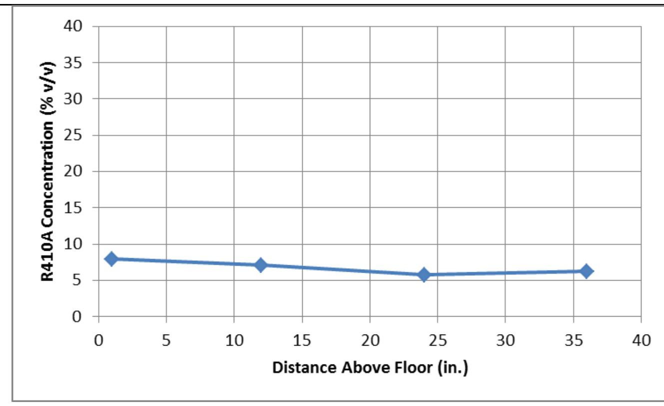
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



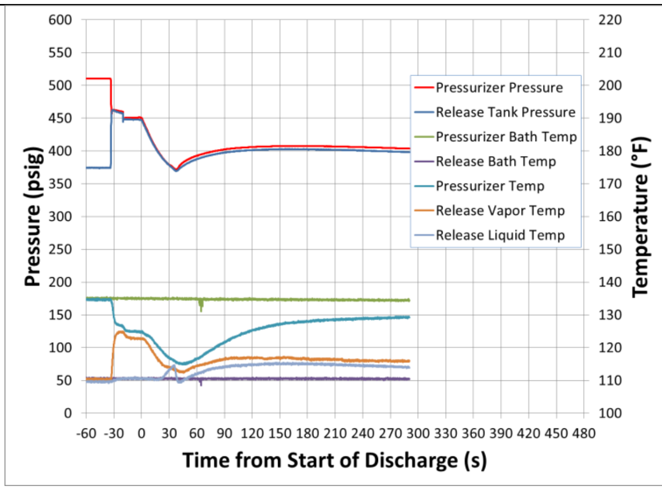
Refrigerant Concentration when Electric arcs are Energized

Figure 77 – Data for PC08

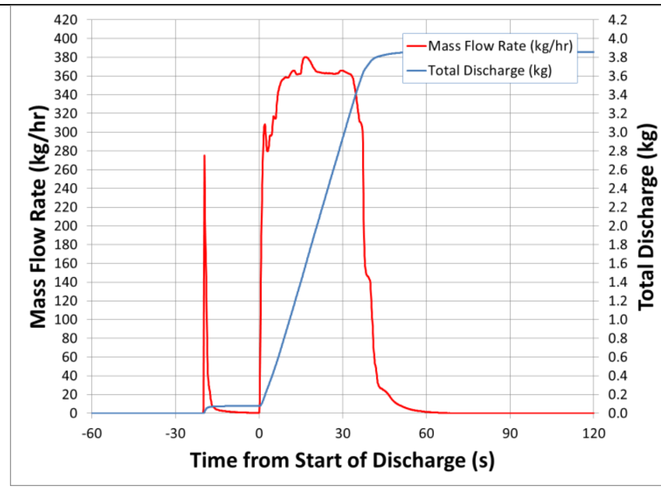
Test PC10: The parameters for the test were as follows:

Refrigerant	Oil Concentration	Ignition Result
R-32	1.5%	Ignition

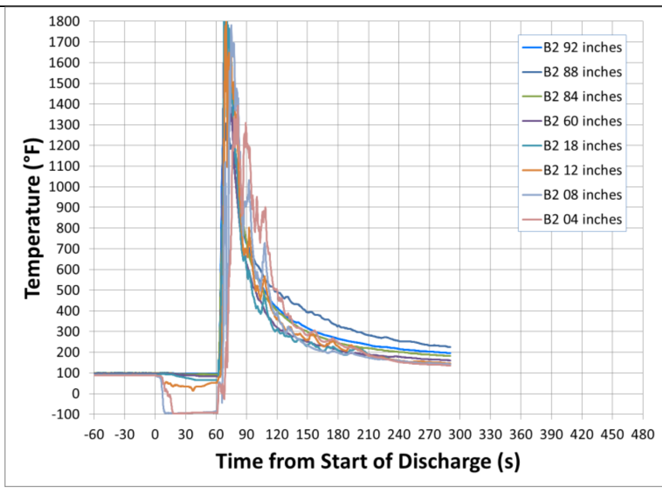
The refrigerant and oil mixture ignited when electric arcs were energized and the flaming continued for 168s. Selected data for the test are presented in Figure 78.



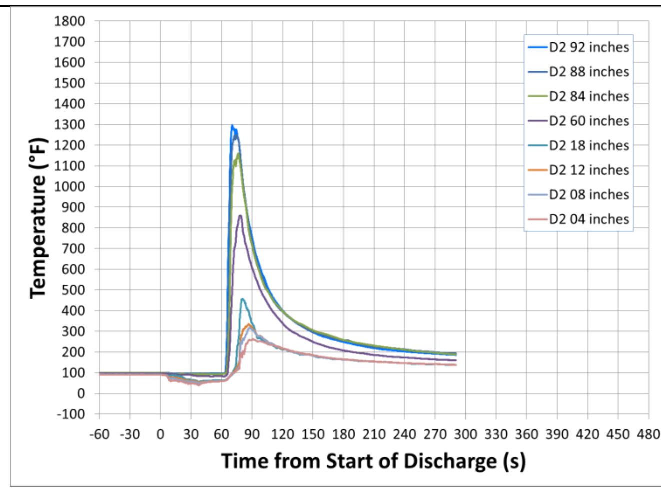
Pressure and Temperature of Release and Pressurizer Tanks



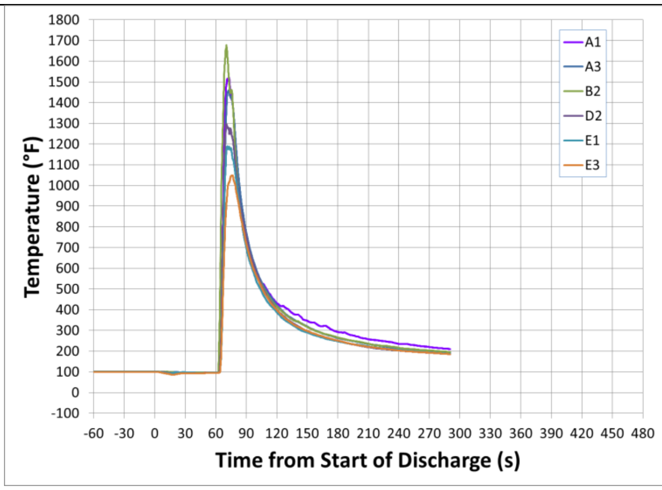
Refrigerant Release Rate



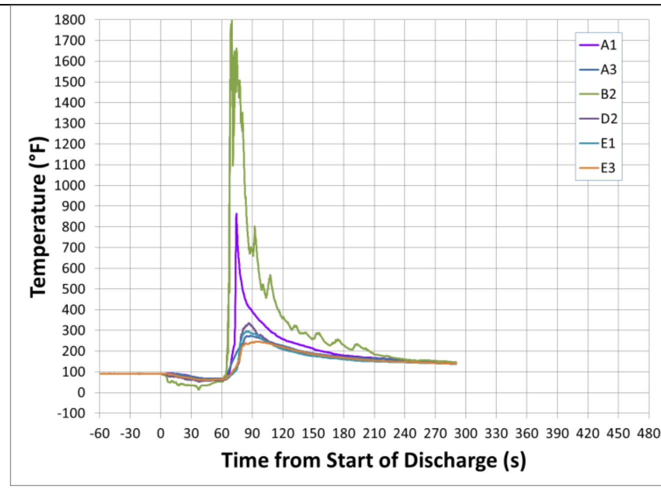
Temperature at Location B2



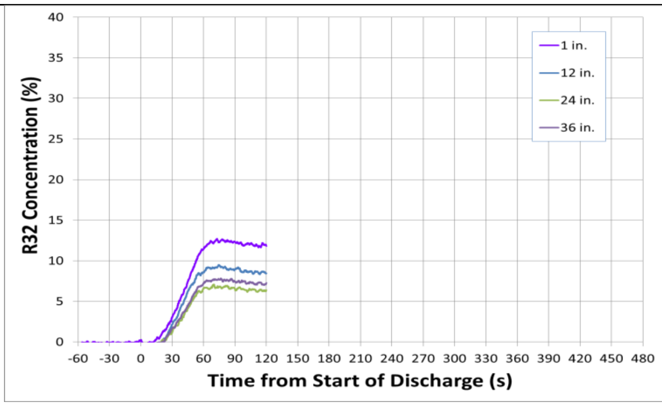
Temperature at Location D2



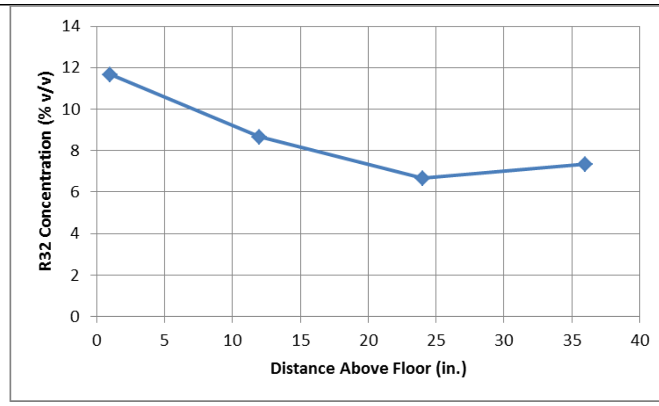
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

End of Release when Electric arcs are Energized

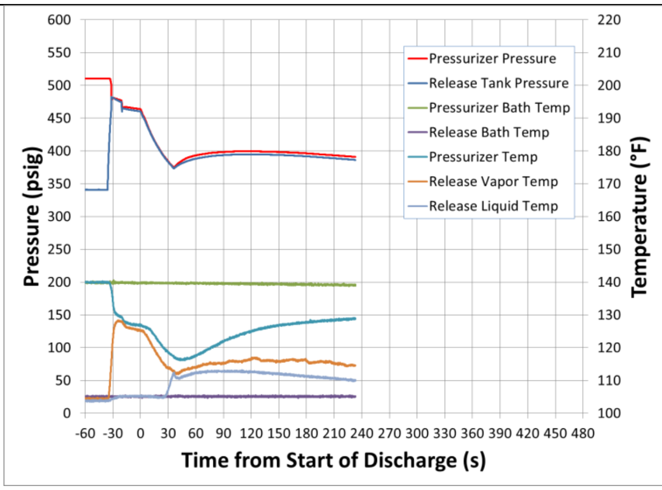
5s after Electric arcs are Energized

Figure 78 – Data for PC10

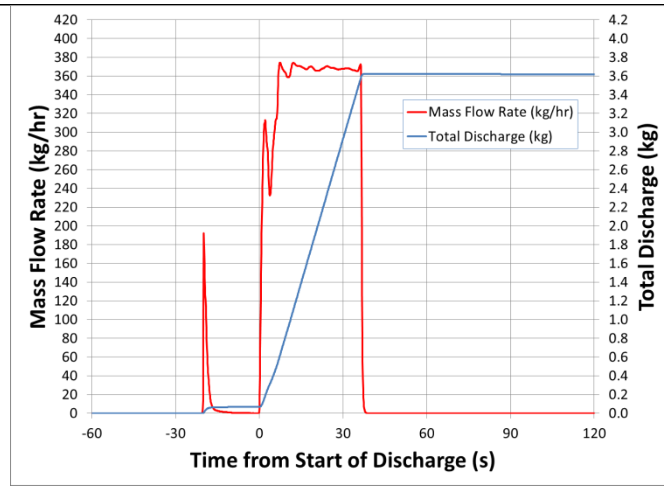
Test PC11: The parameters for the test were as follows:

Refrigerant	Oil Concentration	Ignition Result
R-32	3.0%	Ignition

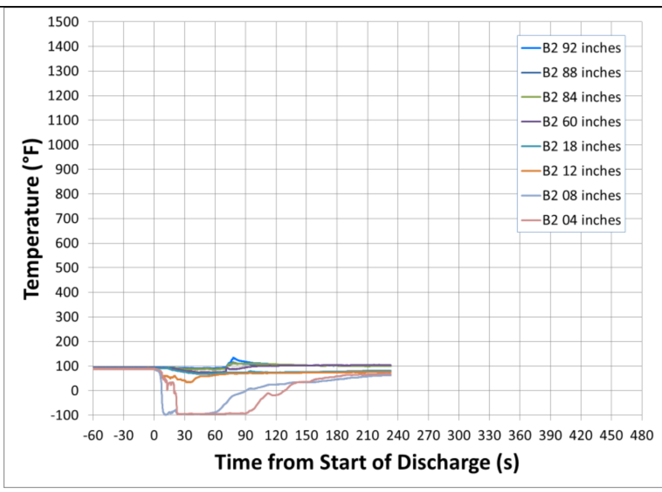
The refrigerant and oil mixture ignited 25s after electric arcs were energized. A blue flame travelled across the floor in front of the location of the electric arcs and the flaming continued for 27s. Selected data for the test are presented in Figure 79.



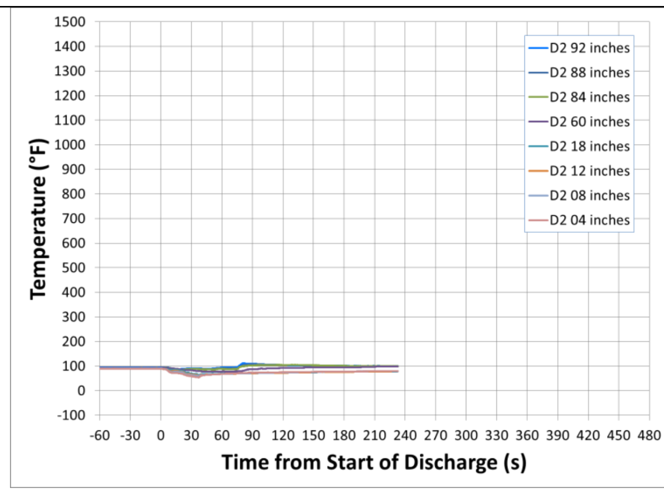
Pressure and Temperature of Release and Pressurizer Tanks



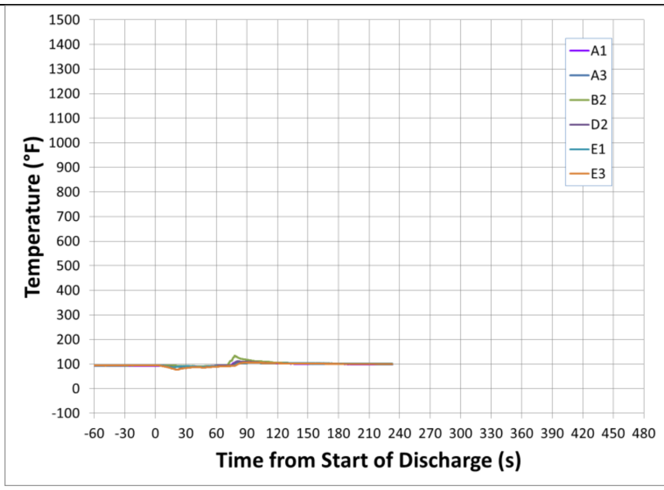
Refrigerant Release Rate



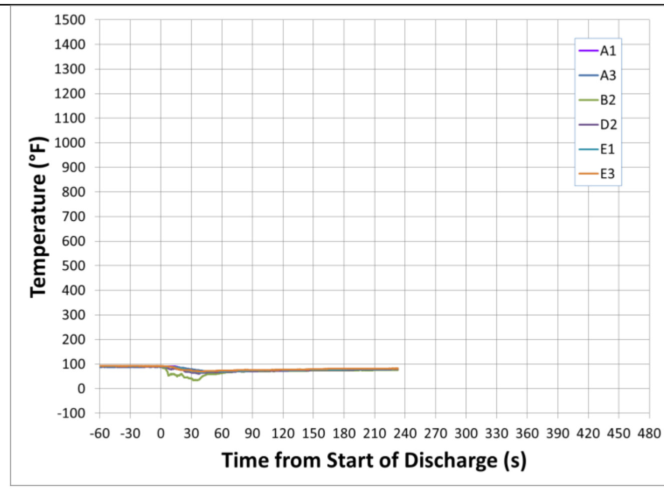
Temperature at Location B2



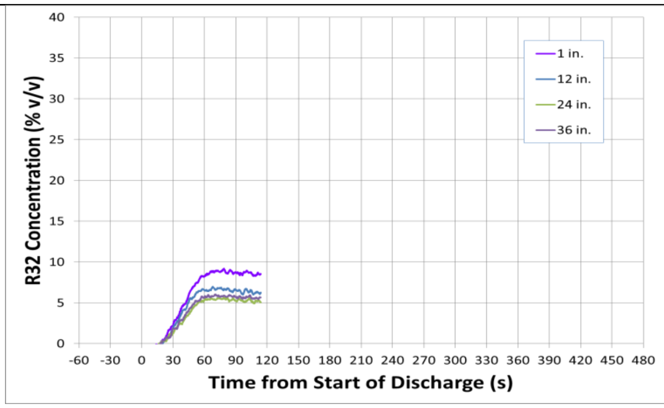
Temperature at Location D2



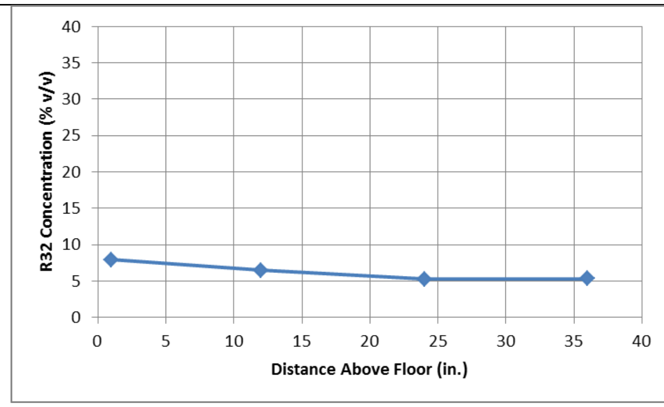
Temperature at 92 in. height above the floor



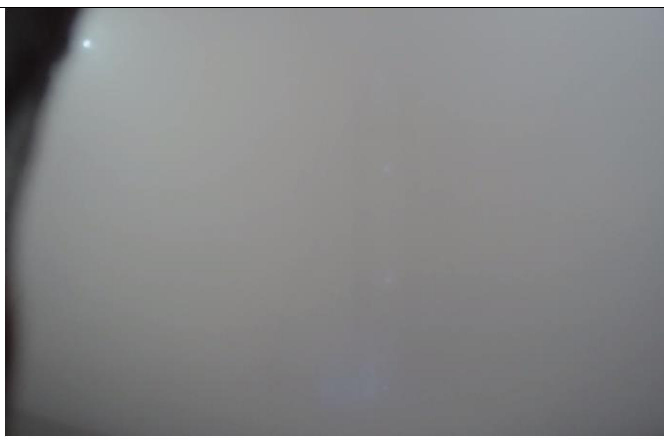
Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized



25s aftter Electric arcs are Energized (blue flame)

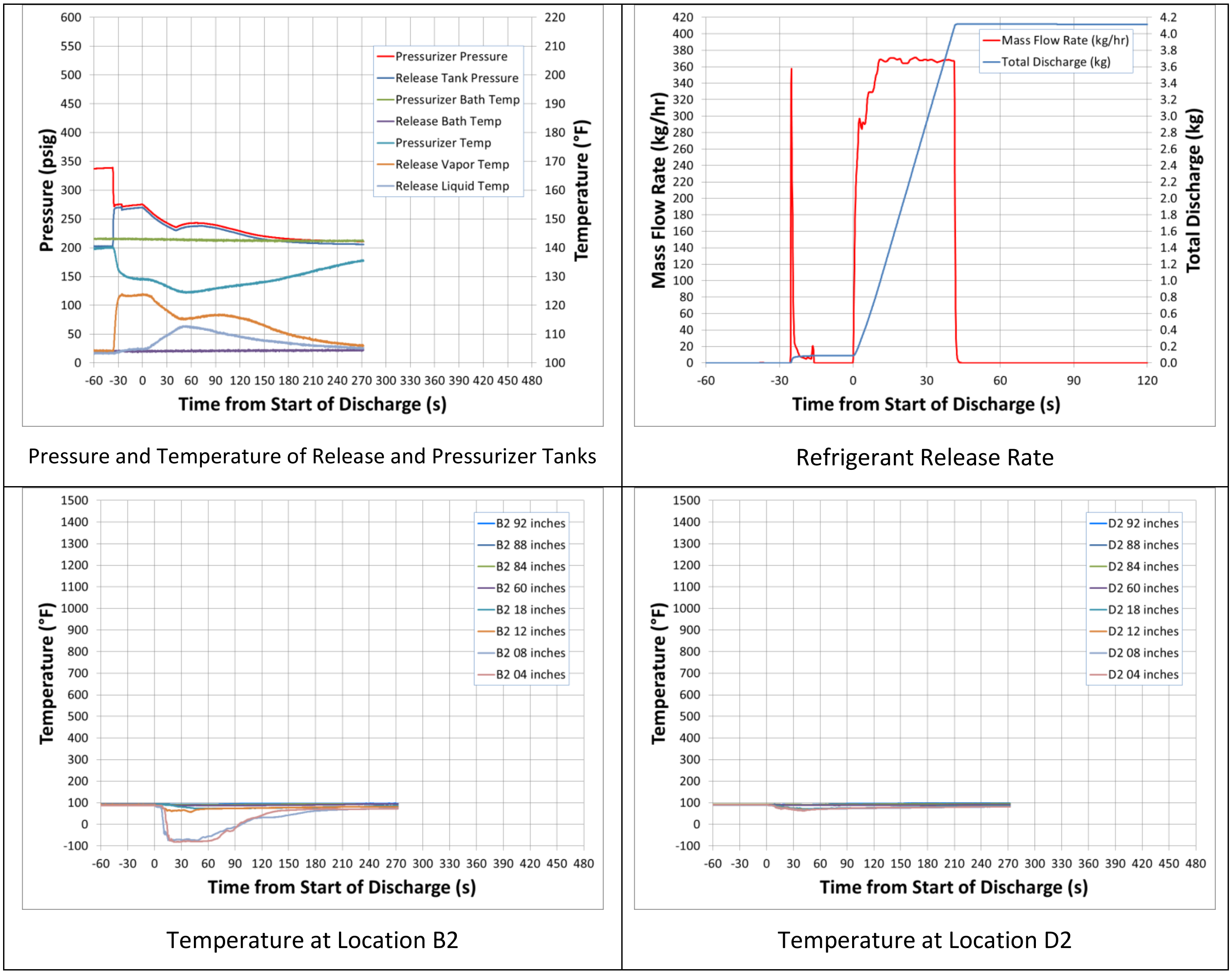
22s after Electric arcs are Energized

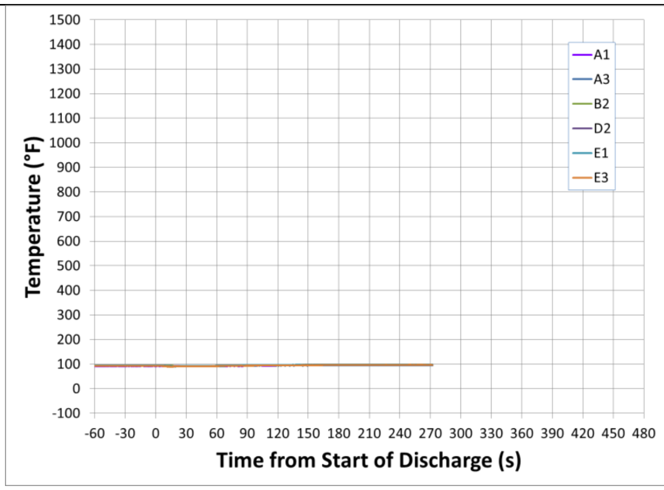
Figure 79 – Data for PC11

Test PC12: The parameters for the test were as follows:

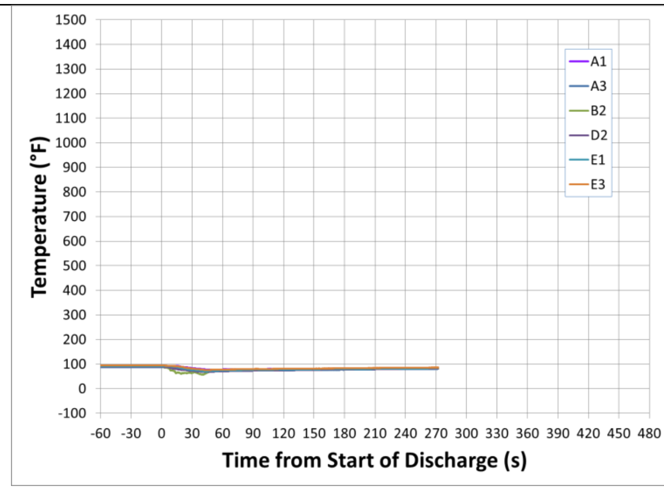
Refrigerant	Oil Concentration	Ignition Result
R-22	1.5%	No Ignition

The refrigerant and oil mixture did not ignite. Selected data for the test are presented in Figure 80.

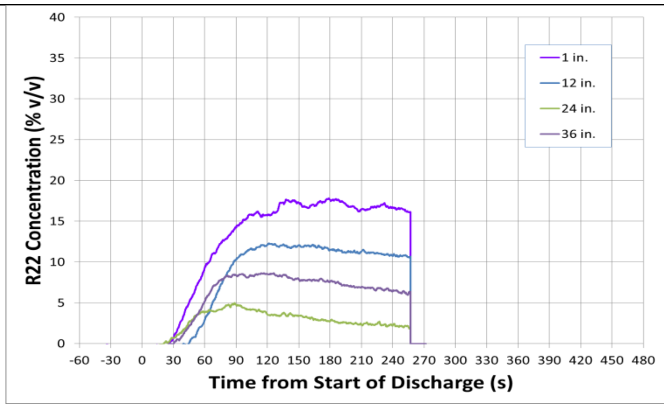




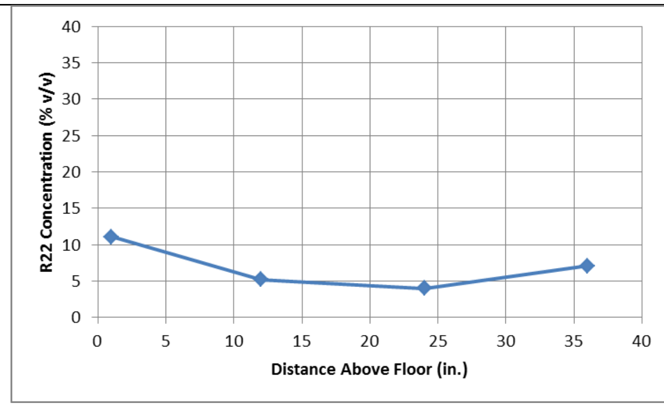
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



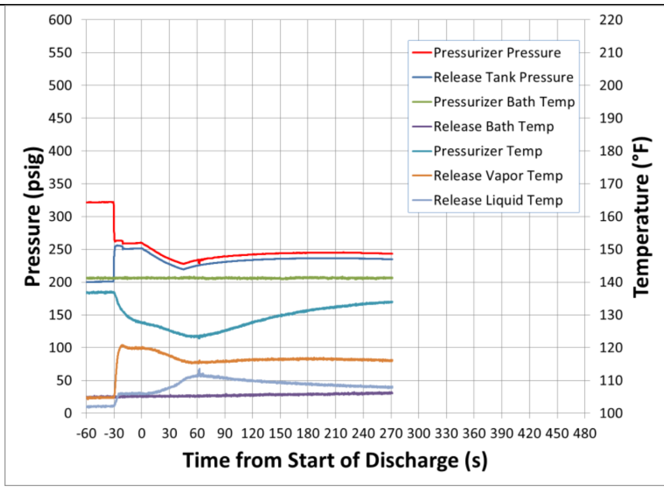
Refrigerant Concentration when Electric arcs are Energized

Figure 80 – Data for PC12

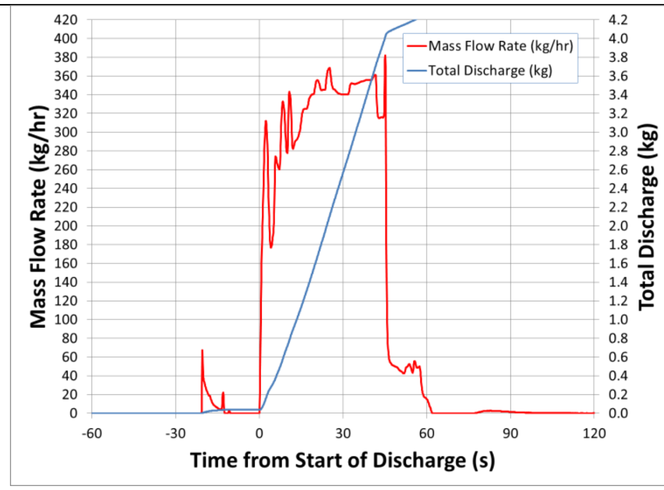
Test PC13: The parameters for the test were as follows:

Refrigerant	Oil Concentration	Ignition Result
R-22	3.0%	No Ignition

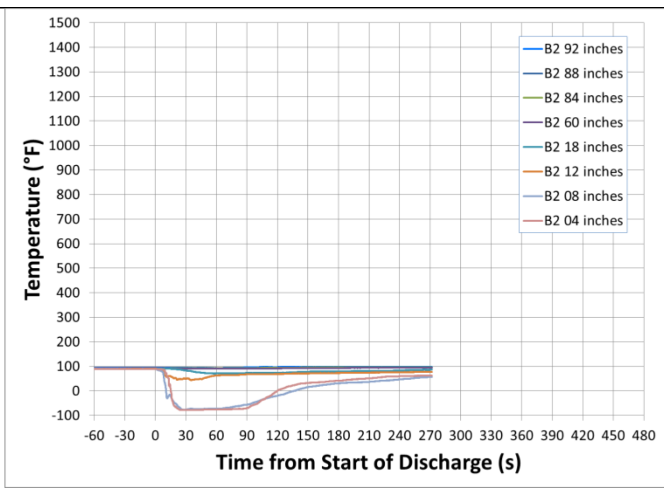
The refrigerant and oil mixture ignited did not ignite. Selected data for the test are presented in Figure 81.



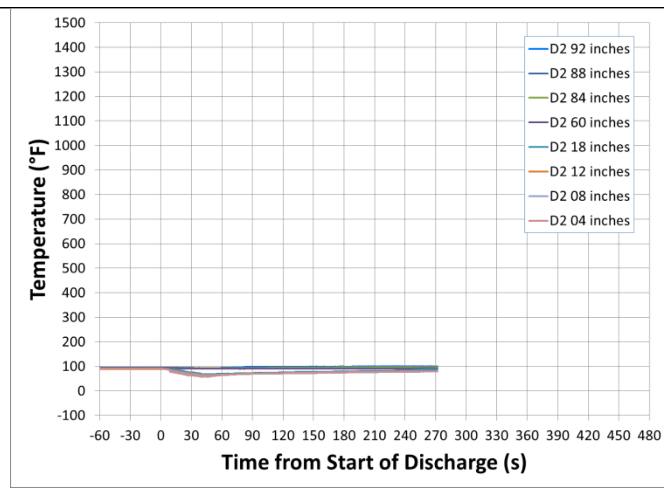
Pressure and Temperature of Release and Pressurizer Tanks



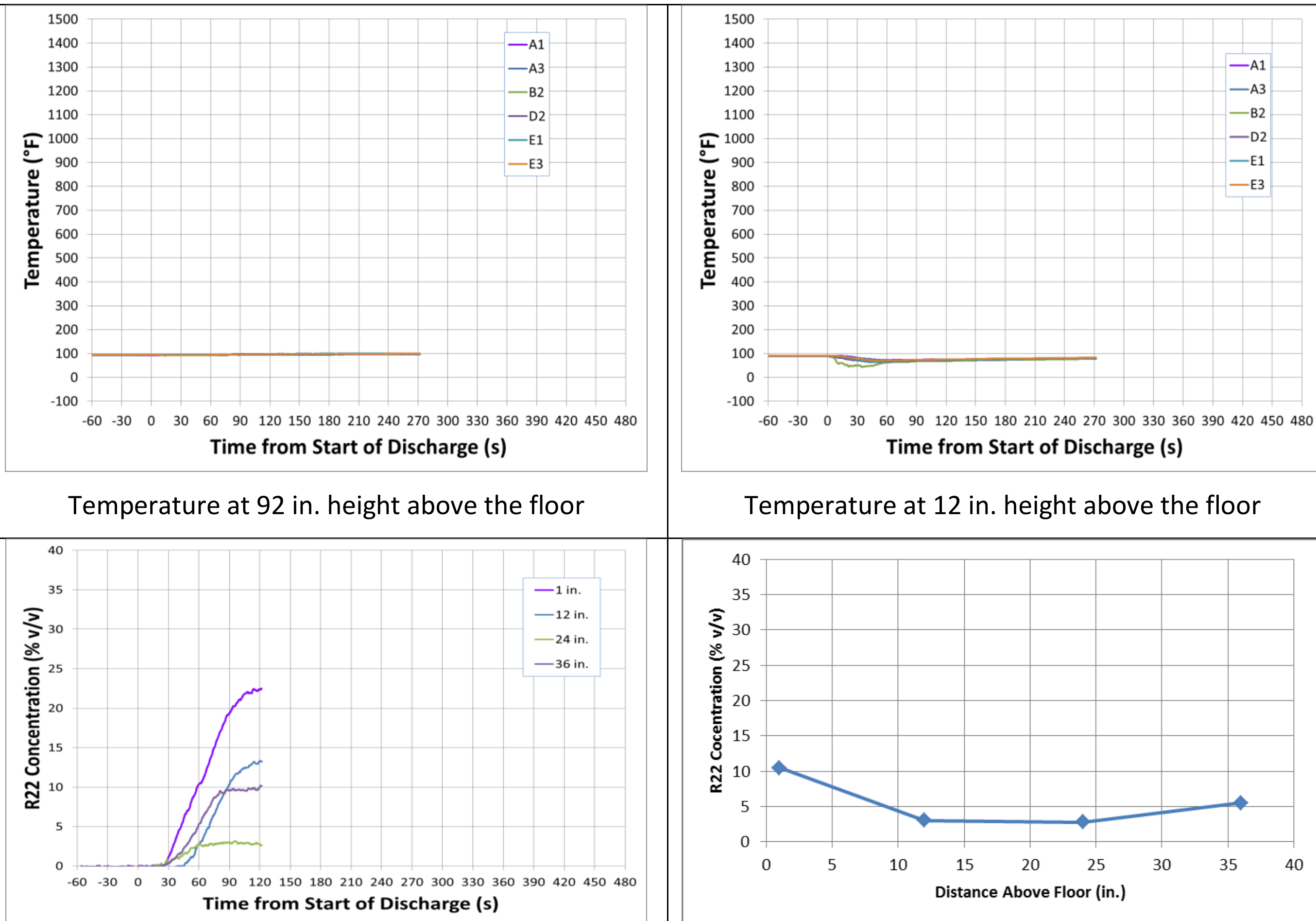
Refrigerant Release Rate



Temperature at Location B2



Temperature at Location D2



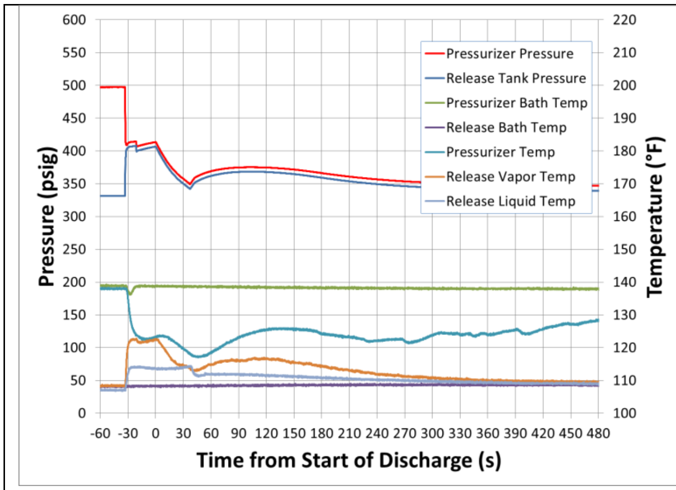
Temperature at 92 in. height above the floor	Temperature at 12 in. height above the floor
Refrigerant Concentration	Refrigerant Concentration when Electric arcs are Energized

Figure 81 – Data for PC13

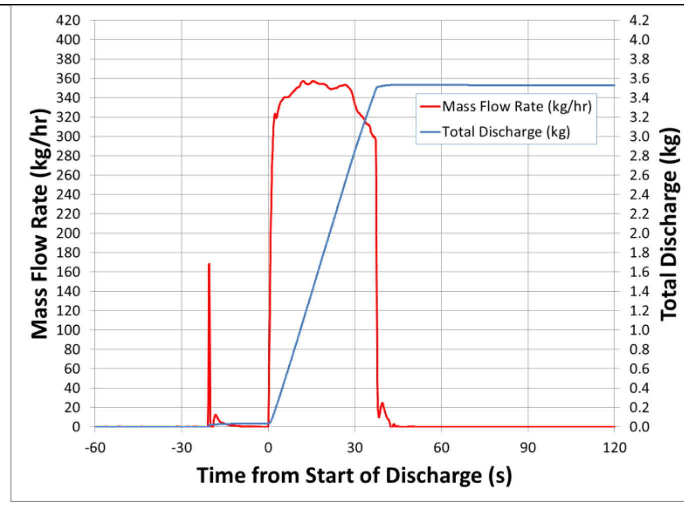
Test PC14: The parameters for the test were as follows:

Refrigerant	Oil Concentration	Ignition Result
R-452B	3.0%	No Ignition

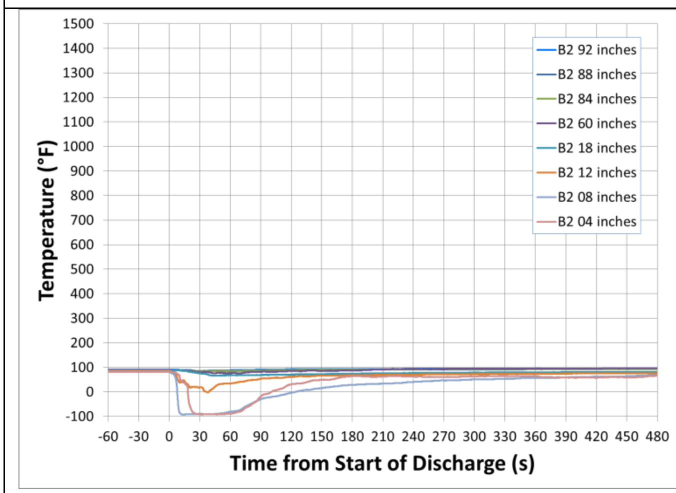
The refrigerant and oil mixture ignited did not ignite. Selected data for the test are presented in Figure 82.



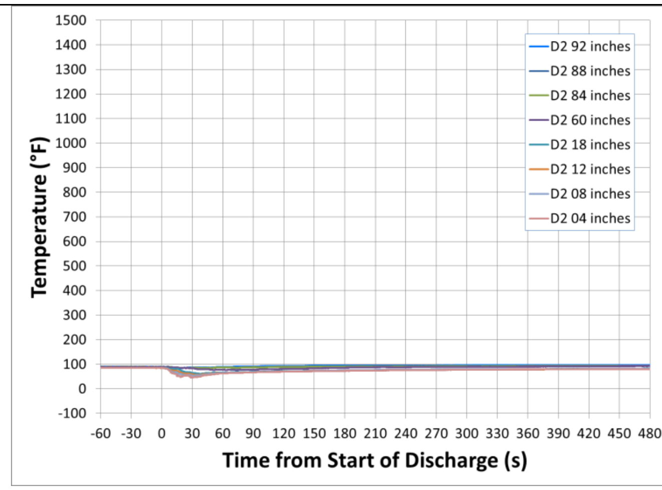
Pressure and Temperature of Release and Pressurizer Tanks



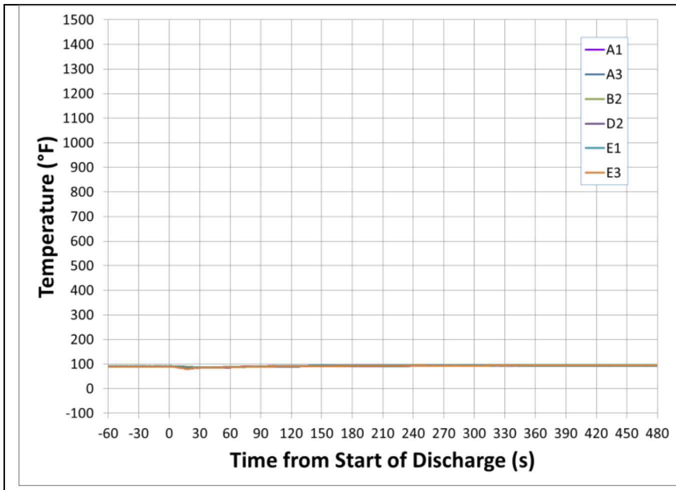
Refrigerant Release Rate



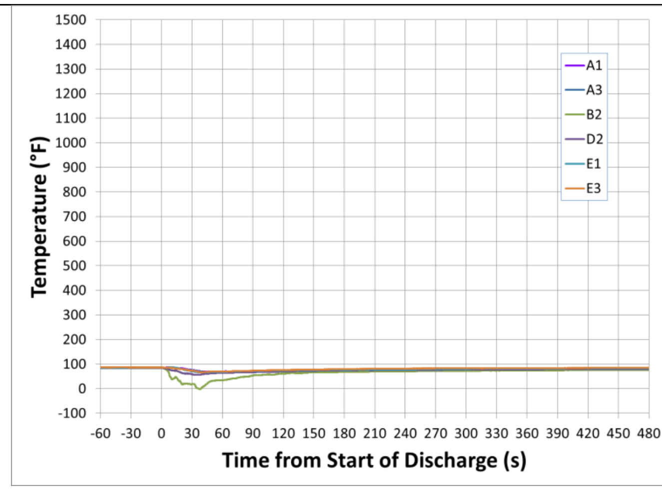
Temperature at Location B2



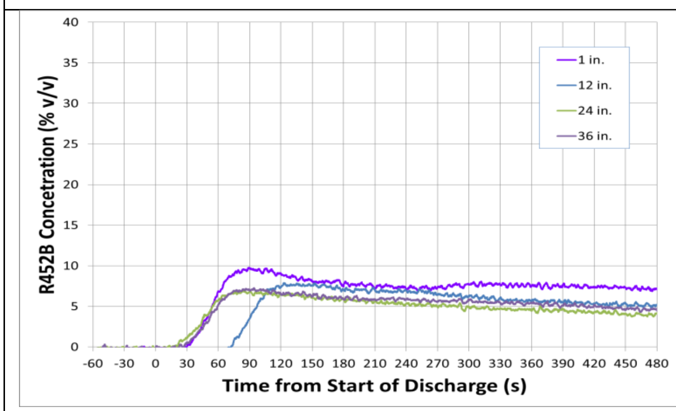
Temperature at Location D2



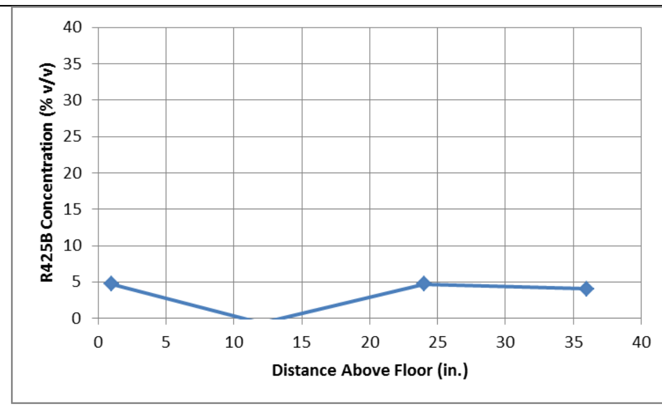
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



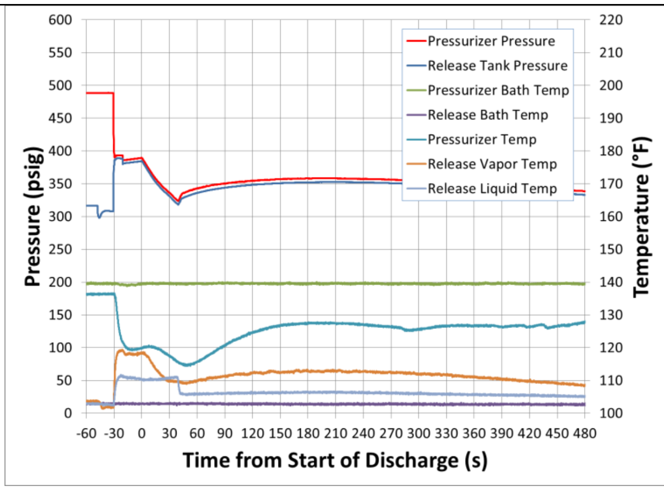
Refrigerant Concentration when Electric arcs are Energized

Figure 82 – Data for PC14

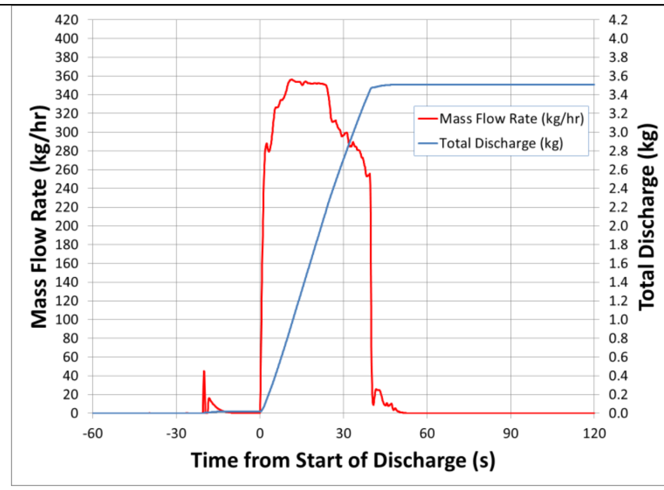
Test PC15: The parameters for the test were as follows:

Refrigerant	Oil Concentration	Ignition Result
R-452B	1.5%	No Ignition

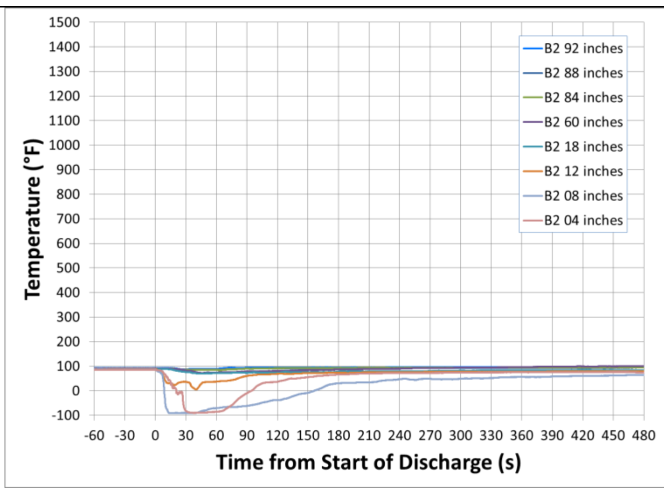
The refrigerant and oil mixture did not ignite. Selected data for the test are presented in Figure 83.



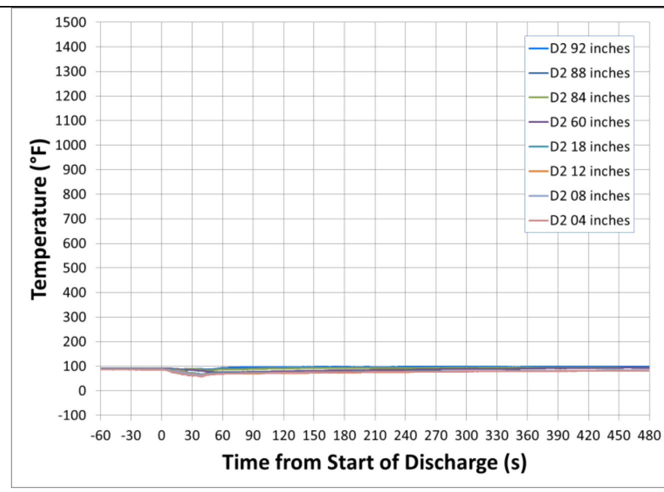
Pressure and Temperature of Release and Pressurizer Tanks



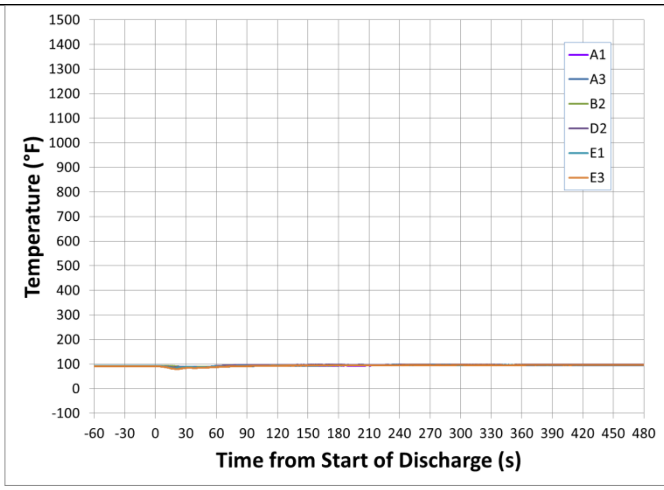
Refrigerant Release Rate



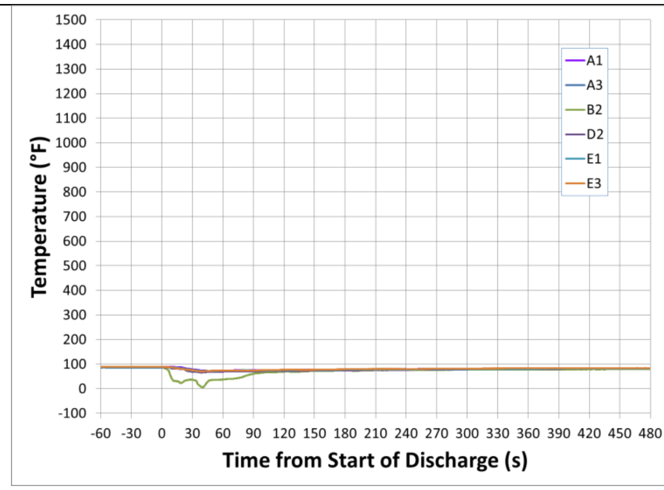
Temperature at Location B2



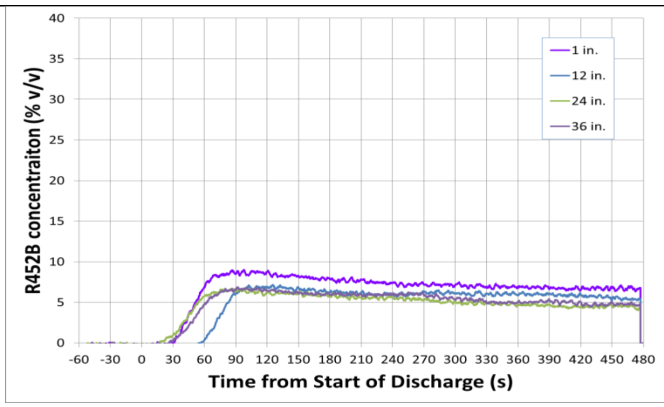
Temperature at Location D2



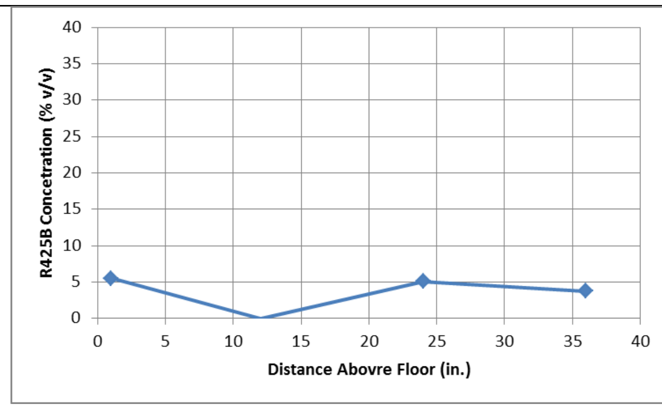
Temperature at 92 in. height above the floor



Temperature at 12 in. height above the floor



Refrigerant Concentration



Refrigerant Concentration when Electric arcs are Energized

Figure 83 – Data for PC15

3.5. Summary of Findings - Task 1

1. Combinations of release rate and opening size that resulted in a low velocity release facilitated the accumulation of a high concentration of refrigerants at the floor (pooling), especially when released near the floor. Combinations of release rate and opening size that resulted in a high velocity facilitated turbulent mixing with room air. When a high velocity stream was released in a high vertical position, the resulting refrigerant concentrations were too low for ignition. When released near the floor, high velocity releases typically ignited, especially with the addition of an obstruction in the release path.
    a. A refrigerant release rate of 100 g/s at a height of 0.2 m through an opening size of 25 mm and with the obstruction resulted in a consistent ignition and flaming of the refrigerant.
    b. For slower flow rates (50 g/sec, 13.5 g/sec) refrigerant pooled at the floor level with concentration higher than the upper flammability limits. However, over time, the refrigerant diffused and mixed with air in the test room and ignited upon energizing the electric arc ignition sources.
2. Obstructions in path of refrigerant release created local concentrations that exceeded the LFL value for the refrigerant and resulting fire in the presence of the ignition source. This was also the case when the total refrigerant release quantity was reduced from 50% LFL to 25% LFL (fully mixed) in the test room. The event severity was notably lower at 25% LFL.
3. 91 °F and 70%RH ambient conditions resulted in higher maximum pressure in the test room; the maximum temperatures were not significantly different.
4. R-32 released with 1.5% and 3.0% oil concentration and without obstruction resulted in a fire event; the temperatures were lower with 3.0% oil concentration. Release of R-452B refrigerant with lubricating oil and without obstruction did not result in ignition. Additional testing is required to gain better understanding of the A2L refrigerant and lubricating oil flammability. Ignition was not observed for R-410A or R-22 refrigerants released in the test room with their lubricant oils.
5. CFD simulation of single phase gas distribution/diffusion can be used to understand and visualize a refrigerant leak event, but does not consider the possibility of two phase flow (liquid and vapor). These experiments showed that liquid refrigerant can be transported and accumulated at a low point. Evaporation of the liquid pool results in high refrigerant concentrations at floor level.

4. Task 2 – Scenario Tests: Refrigerant Leak and Ignition Testing at Whole Room Scale

Equipment was provided by AHRTI for use in leak and ignition testing in scenario based tests. A description of the equipment, refrigerants, and scenarios is shown in Table 20. The table also shows the number of valid tests conducted and a short summary of the results. See the following sections for a complete description of each scenario and test results.

Table 20 – Whole Room Scale Scenarios and Summary

Scenario	Equipment	Refrigerants	Number of Tests	Result
Commercial Kitchen	Roof top Unit	R-32 R-452B	5	No ignition
Motel Room	PTAC Unit	R-32 R-452B	9	Either No ignition Or Enhanced flaming at candle locations
An Experiment Requested by PMS	Modified PTAC	R-32	1	Ignition of refrigerant jet localized at floor level
Residential	Split A/C system Coil failure	R-32 R-452B	5	Ignition
Residential	Split A/C system Servicing Error	R-32 R-452B R-410A	3	Localized ignition at break point
Residential	Compressor/ Condenser Hermetic Electrical Pass-Through Terminal failure	R-32 R-452B R-410A	4	No ignition in 3 tests Ignition in 1 test
Convenience Store	Reach in cooler	R-455A R-457A	4	No ignition in 1 test Ignition in 3 tests.
Convenience Store	Walk in cooler	R-455A R-457A	7	Flames to ceiling in 2 tests Flaming at floor level in 2 tests No ignition in 3 tests

4.1. Refrigerants

Properties of the refrigerants used are shown in Table 1. The discharge quantities varied with each scenario and are discussed in each scenario.

4.2.Test Facility

The testing was conducted in UL's 45 x 45 x 40-ft. high test facility in the large-scale fire test area. The facility was connected to a smoke abatement system to combust particulates and unburned gases. The 30 x 30 x 8-ft. high test area from Task 1 was used to construct scenario rooms within this area.

4.3.Instrumentation and Data Acquisition

The instrumentation and video equipment used in Task 1 (refer to the Task1 section on ***Instrumentation***) was also deployed in the scenarios in Task 2. The following sections provide the specific deployments in each scenario. Full specifications of instrumentation and equipment used throughout this project are included in Appendix D Test Instrumentation and Equipment.

Following the first set of Task 2 experiments (Motel Room with PTAC) additional safety measures were implemented as described in the following:

Figure 84 shows the addition of two solenoid valves. The solenoid valves were remotely to enable a positive shutoff of refrigerant flow at the end of the discharge. The refrigerant solenoid directly blocked the refrigerant discharge line until activated remotely. When energized, the air solenoid allowed the control air to pass through to the control valve. When de-energized, the control air signal was blocked and the pressure on pneumatic actuator was removed causing the valve to close by spring action.

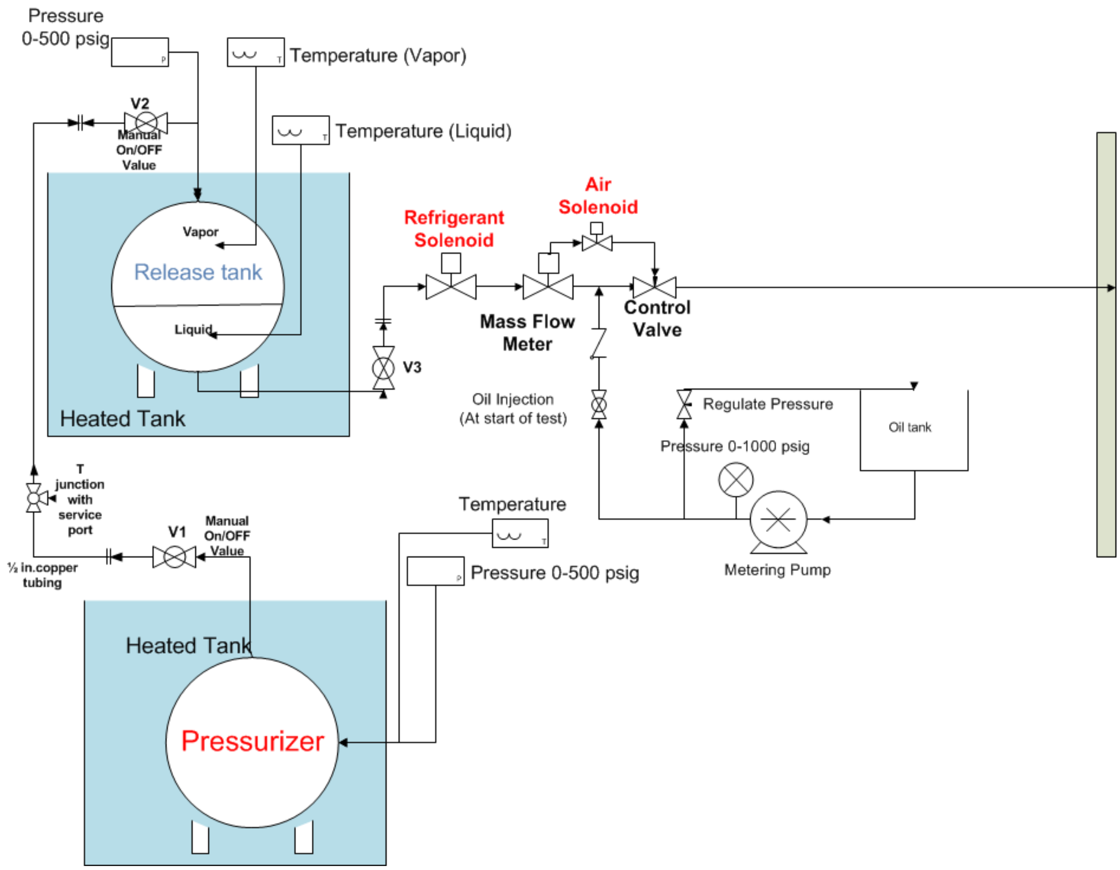


Figure 84 –Refrigerant Release and Oil Injection system with remotely operated solenoid valves

4.4. Ignition Sources

The ignition sources used in the scenario tests were external to the air conditioning or refrigeration devices.

The electric arc ignition sources were identical to those used in Task 1.

Tea candles were 1-1/2 in. in diameter. The tea candles were ignited either remotely using matches ignited with heated nichrome wire or manually prior to the test. The tea candle and igniter are shown in Figure 85. The igniter system was inconsistent and so, after the first few tests, the candles were lit at the beginning of the test

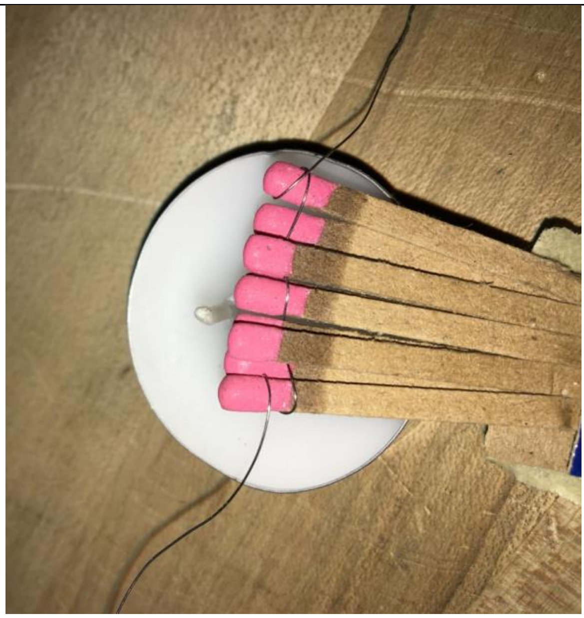
	
Tea candle	Tea candle with match-nichrome wire

Figure 85 – Tea Candle

4.5. Commercial Scenarios

4.5.1. Motel Room Scenario

The motel room scenario involved the use of a Package Terminal Air Conditioner (PTAC) in a motel room layout. The test setup for the motel room is shown in Figure 86, Figure 87, Figure 88, Figure 89, and Figure 90. The motel room dimensions were 13 x 16 x 8-ft. (4.0 x 4.9 x 2.4m) high. An object representing a bed was located in the test area.

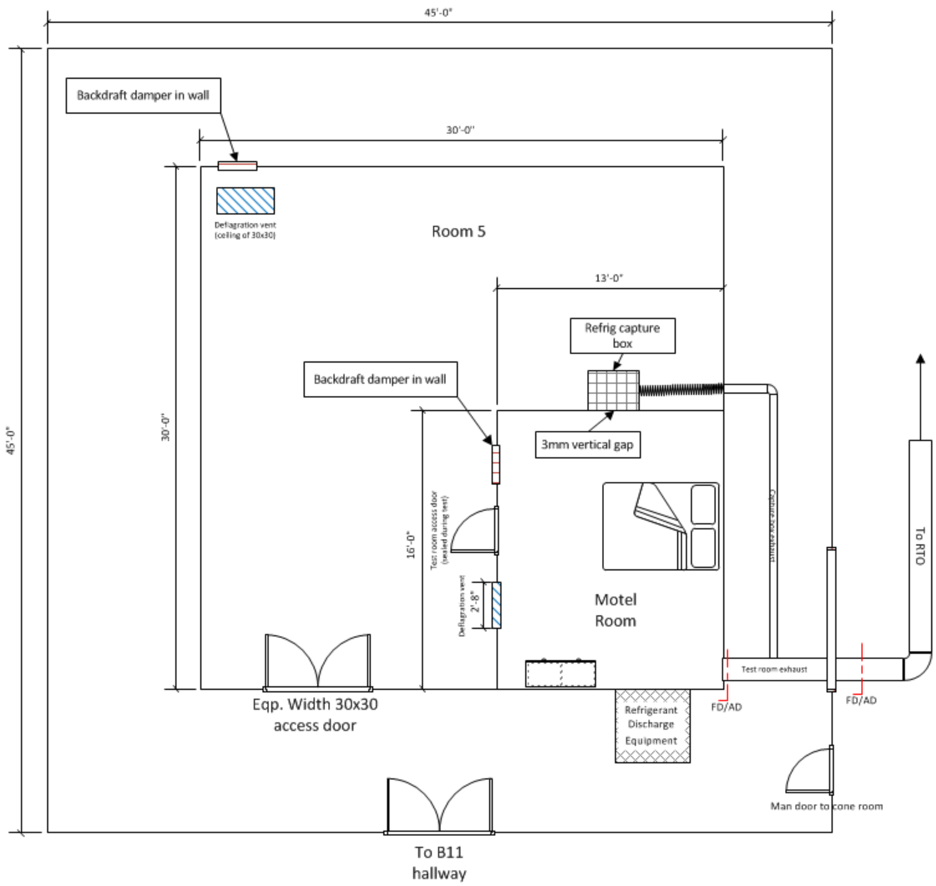


Figure 86 – Motel Room Layout within the 30'x30' test room

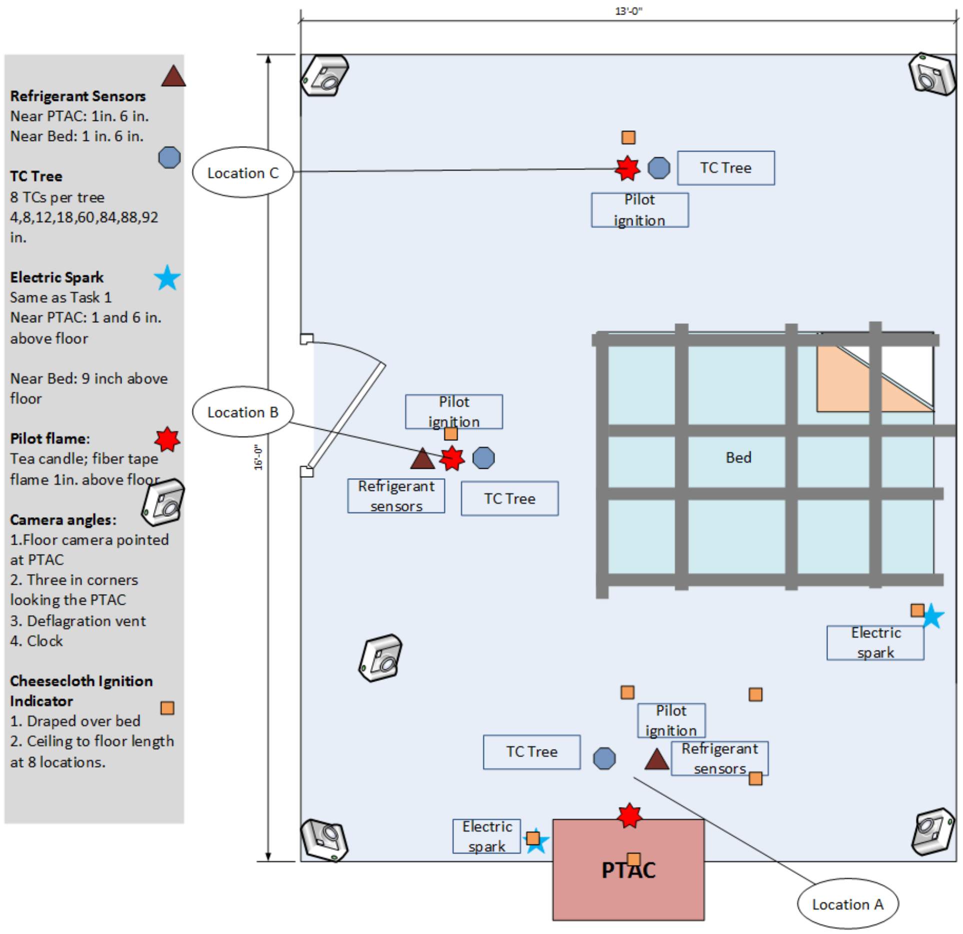


Figure 87 – Larger view of motel room detail

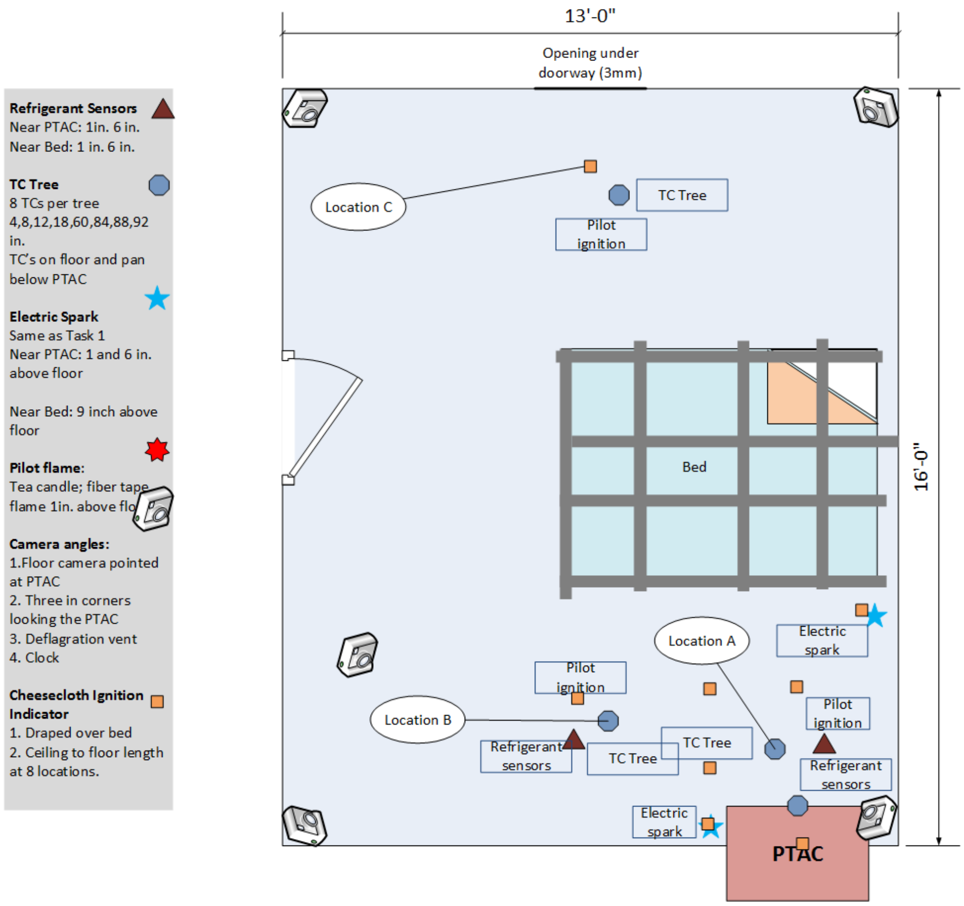


Figure 88 – Motel Room Configuration for tests PTAC11, PTAC12, and MPTAC01

Figure 89 - Camera view of PTAC mounted in the center of the wall

Figure 90 – PTAC installation in test MPTAC01. The PTAC is positioned 3 inches away from the side wall.

The PTAC unit had dimensions of 48 x 16 inches (width and height) (1.2m x 0.4 m). The unit was mounted with a wall sleeve that was flush with the finished interior wall surface.

The locations of the instrumentation, and ignition sources were located in clusters at locations A, B, and C. The locations relative to the front and right walls are shown in Table 21. These locations apply to tests PTAC04 through PTAC08. Tests PTAC09-PTAC12 and MPTAC01 had different arrangements of instrumentation. Those arrangements are discussed in PTAC09, PTAC11, and MPTAC01 results discussion.

Table 21 – Location of Instrumentation and Ignition Sources

Item	Location	Number	Height above Floor (in.)	Distance from front wall (ft.)	Distance from right wall (ft.)
Refrigerant sensor	A	2	1, 6	1.5	6.5
	B	1	1, 6	8	10
Thermocouples	A	8	4, 8, 12, 18, 60, 84, 88, 92	1.5	6.5
	B	8	4, 8, 12, 18, 60, 84, 88, 92	8	10
	C	8	4, 8, 12, 18, 60, 84, 88, 92	14	6.5
Pilot flame	A	1	1	1.5	6.5
	B	1	1	8	10
	C	1	1	14	6.5
	Under PTAC	1	37	8 inches	6.5
Electric arc	Side of PTAC	2	1, 6	2 inches	8
	Side of Bed	1	6	5	2 inches

4.5.1.1. Refrigerant Release

The release quantities were set at 1.81 kg for R-32 and 1.82 kg for R-452B. The refrigerant quantity released in the tests corresponds to proposed m_1 size charge of $(6\ m^3 \times LFL\ \frac{kg}{m^3})$ where LFL is the lower flammable limit in kg/m³ from for the refrigerant used (as proposed for future edition of IEC 60335-2-40 [12] in sub clause GG.1.1 and future adoption in North America). For the typical motel room size selected for this project (1660 ft³, 47.1 m³), this quantity of refrigerant is equivalent to an average concentration that is approximately 13% of the LFL if the refrigerant would be completely mixed in the test room volume. The PTAC fan was not energized.

The refrigerant leak was created by placing a ¼ inch tube in the center of the coil face. The length of the tube was approximately 3 meters and was attached to a 1 by ¼ inch reducer at the exit of the mass flow control valve. The first two tests (PTAC04 and PTAC05) were for the purpose of determining the time of that maximum refrigerant concentration. The next three tests (PTAC06-PTAC08) used the data from the first two tests to determine an appropriate time to ignite the candles and electric arcs. Two additional tests (PTAC09 and PTAC10) were completed with the candles and electric arcs lit before the discharge was started

The refrigerant leak location was moved to the far left side (nearest wall) of the coil face for tests PTAC09-PTAC12. In tests PTAC11, PTAC12, and MPTAC01, the PTAC unit was relocated to be 3 inches from the adjacent wall. Three inches was selected as it is the minimum distance specified by the installation instructions.

An additional test, MPTAC01, was conducted for the purpose of igniting the refrigerant jet closest to the end of the discharge tube.

Table 22 – PTAC experimental matrix

Refrigerant	Test Number	Planned Discharge (kg)	Discharge Rate (g/s)	Discharge Tube location	PTAC Location
R-32	PTAC04	1.81	50	Coil Face Center	Centered on Wall
R-452B	PTAC05	1.82	50	Coil Face Center	Centered on Wall
R-32	PTAC06	1.81	50	Coil Face Center	Centered on Wall
R-452B	PTAC07	1.82	50	Coil Face Center	Centered on Wall
R-32	PTAC08	1.81	50	Coil Face Center	Centered on Wall
R-32	PTAC09	1.81	50	Coil Face Far Left	Centered on Wall
R-452B	PTAC10	1.82	50	Coil Face Far Left	Centered on Wall
R-452B	PTAC11	1.82	50	Coil Face Far Left	3 in. from side wall
R-32	PTAC12	1.81	50	Coil Face Far Left	3 in. from side wall
R-32	MPTAC01	1.81	50	Coil Face Far Left	3 in. from side wall

4.5.1.2. Test Procedure

The following procedure was used to initiate each test:

1. Confirm pressurizer and release refrigerant tank pressures and temperatures.
2. Develop vacuum (less than 1mm Hg) in piping connecting the pressurizer and release tanks and between the release tank and flow meter.
3. Confirm the test room temperature and humidity are at 91±3°F and 70±5% relative humidity.
4. (Tests PTAC09-10 and MPTAC01) Light the candles, turn on electric arcs, and turn off the lab HVAC and humidity systems.
5. Initiate data acquisition and video capture 1 minute prior to discharging refrigerant.
6. Open the valve between the pressure and release tanks, and hold for 5 seconds.
7. Open the valve between release tank and the flow meter and hold for 5 seconds.
8. Open the control valve to initiate refrigerant discharge through the mass flow meter.
9. (Tests PTAC04-08) After the discharge is complete, ignite candles remotely and turn on the electric arcs.
10. Continue to collect data until all flaming has ceased for at least 2 minutes.
11. Vent the test room.

After each test, the test facility was exhausted through UL's smoke abatement system, and the conditions in the facility were monitored with open path gas FT-IR. Staff re-entered the test facility only after the gas FT-IR indicated normal ambient conditions.

4.5.1.3. Summary of Findings – Motel Room and PTAC Tests

The PTAC tests were designed to simulate the release of refrigerant in a typical motel room with ignition devices representing those sources that could be expected to occur. In some of the tests, ignition sources were not used in order to measure the resulting refrigerant concentrations. The ignition sources used were tea candles or electric arcs at various locations. Refrigerant concentrations measured in PTAC tests 04 through 12 did not show values above the LFL and ignition was not expected. One test, PTAC07 using R-452B resulted in a low energy and short duration ignition lasting no more 3 seconds. There was no secondary ignition of the cheesecloth.

4.5.1.3.1. Tests with R-32

The location and direction of the R-32 discharge appeared to have significant effect on the resulting refrigerant concentrations. Figure 91 shows the deconvoluted R-32 concentrations for five tests using the measurement location with the highest peak concentration. The following points can be gleaned from the videos of these five tests:

- In PTAC04 the discharge from the center of the coil face is primarily directed down to the floor and resulted in highest concentrations.
- In PTAC06 and PTAC08 the discharge from the center of the coil face is primarily directed horizontally to the right and resulted in greater mixing and lower concentrations.

- In PTAC09 the discharge from the left side of the coil face was directed primarily toward the floor. This resulted in higher concentrations than in tests 6 and 8, but the video shows a sweeping action which directed the refrigerant away from the front of the PTAC and resulted in lower concentrations than in PTAC04.
- In PTAC12 the PTAC was moved to the far left of the room as shown in Figure 88. The discharge tube remained on the left side of the PTAC unit. Similar to PTAC09, the discharge jet initiated a momentum driven circulation in the room that swept refrigerant away from the front of the PTAC. The peak refrigerant concentration was lower than the four other tests.

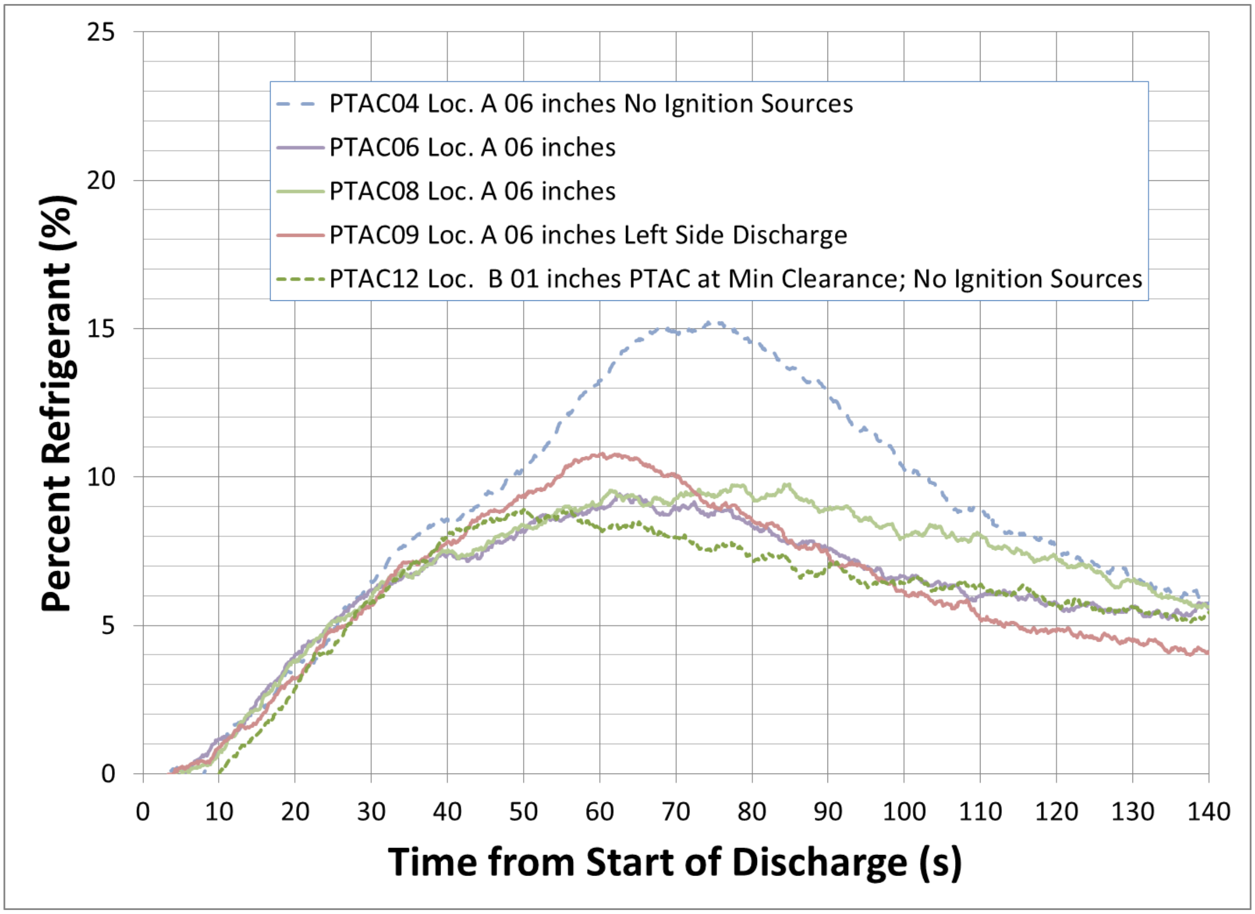


Figure 91 – Comparison of R-32 concentrations

4.5.1.3.2. Tests with R-452B

The location and direction of the R-452B discharge did not appear to have a significant effect on the resulting refrigerant concentrations. This result is in contrast to the R-32 results which did show a significant effect. Figure 92 shows the deconvoluted R-452B concentrations for five tests. Figure 93 shows a comparison of frames taken at 35 seconds after the start of refrigerant release. In test PTAC07, the video documentation shows more mist accumulating at the A location (in front of the PTAC).

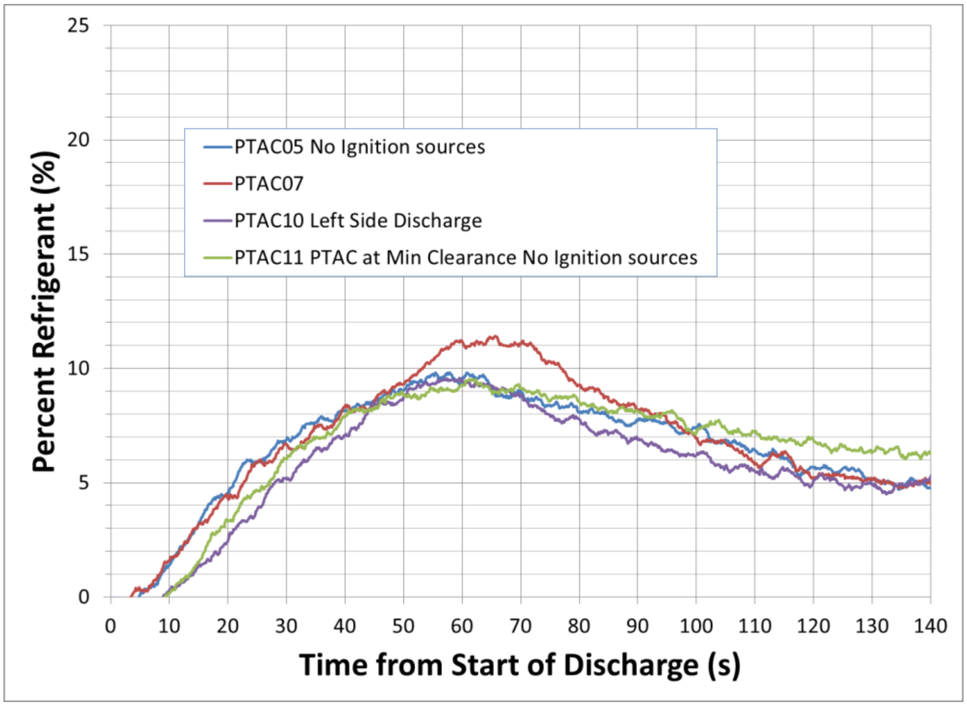


Figure 92 – Comparison of R-452B concentrations

Figure 93 – Comparison of R-452B videos at 35 seconds after the start of release

4.5.1.3.3. *Ignition Sources*

The initial guidance from the project management subcommittee directed that the candles and electric arcs would not be ignited until after the refrigerant release was initiated. The electric arcs were located on the walls and did not result in additional flaring due to the presence of refrigerant.

The tea candles were difficult to ignite remotely in a consistent manner. In some cases, the candles were extinguished either by cooling and refrigerant movement or possibly by high refrigerant concentrations. In other tests, the remote ignition system failed to ignite the candles or was delayed. Beginning with test PTAC09, the candles were pre-lit before the beginning of the test. In both PTAC09 and PTAC10, one candle was extinguished during the refrigerant release.

4.5.1.4. *Results*

Table 33 and Table 24 show a summary of the 10 tests conducted in this scenario.

Table 23 – Motel Room Scenario Summary

Refrigerant	Test Number	Igniter Condition	Max Pressure (mmHg)	Max. Temperature / Location and Height (°F /Location)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	Result
R-32	PTAC04	None	0.01	92 / C92	92	91	Only concentrations measured
R-452B	PTAC05	Note	0.01	97 / C92	97	95	Only concentrations measured
R-32	PTAC06	@56 sec	0.01	101 / A92	101	98	No Ignition
R-452B	PTAC07	@56 sec	0.01	104 / A92	104	97	Small Ignition (3 seconds)
R-32	PTAC08	@20 sec	0.01	106 / C18	97	95	No Ignition
R-32	PTAC09	Pre-lit	0.01	119 / C08	98	97	No Ignition
R-452B	PTAC10	Pre-lit	0.01	120 / C04	99	97	No Ignition
R-452B	PTAC11	None	0.01	96 / C92	96	93	Only concentrations measured
R-32	PTAC12	Note	0.01	99 / C92	99	96	Only concentrations measured
R-32	MPTAC01	Pre-lit	0.47	439 / A92	439	337	Ignition

Note: Results labeled as “Concentrations” were tests without ignition sources.

Table 24 – Motel Room Discharge Mass, Rate, and Maximum Concentration

Refrigerant	Test Number	Measured Discharge (kg)	Planned Discharge (kg)	Measured Rate (g/s)	Maximum Refrigerant Concentration Measured (%)
R-32	PTAC04	1.98	1.81	44.7	15.2
R-452B	PTAC05	1.88	1.82	48.0	9.8
R-32	PTAC06	1.87	1.81	37.3	9.4
R-452B	PTAC07	1.92	1.82	47.4	11.4
R-32	PTAC08	2.07	1.81	46.6	9.8
R-32	PTAC09	1.78	1.81	42.6	10.8
R-452B	PTAC10	1.88	1.82	45.2	9.6
R-452B	PTAC11	2.06	1.82	47.1	9.5
R-32	PTAC12	1.96	1.81	46.7	8.9
R-32	MPTAC01	2.95*	1.81	23.1*	31.0

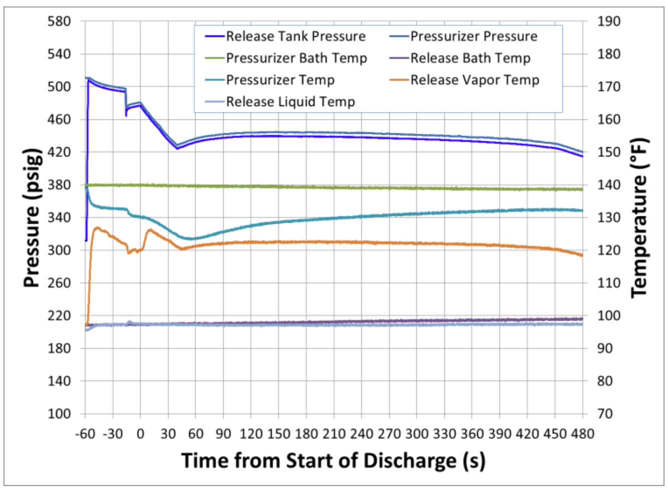
* -- In test MPTAC01, the refrigerant mass flow control valve failed to close completely. The manual valves were used to stop the flow 96 seconds after the discharge should have been completed. The higher release quantity corresponded to 21% of LFL if fully mixed into the room.

4.5.1.4.1. *PTAC04:*

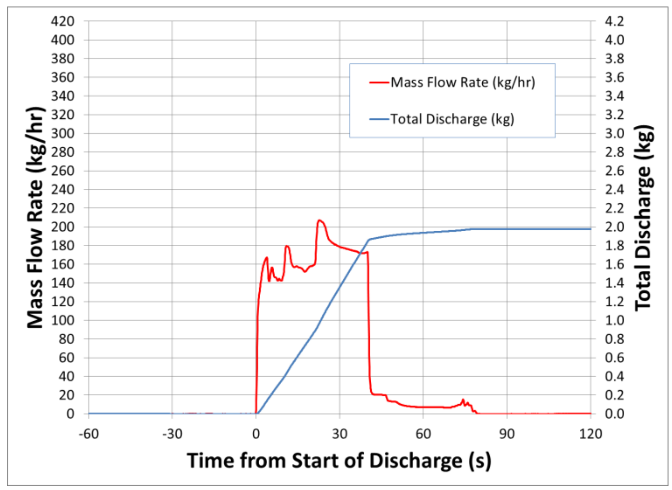
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Candle and Electric arc Ignition Time	Ignition Result
R-32	50	1.81	Not Applicable	No ignition

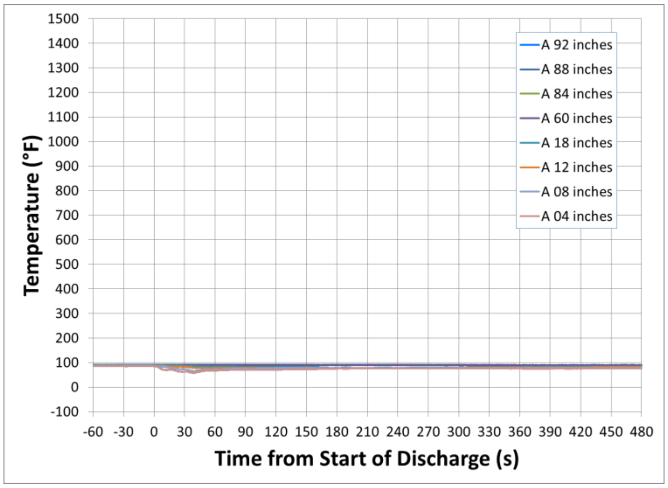
The purpose of this test was to determine the time that R-32 refrigerant concentration was at its maximum value. This data was then used to determine electric arc and candle ignition time in subsequent tests. Selected data from this test are shown in Figure 94.



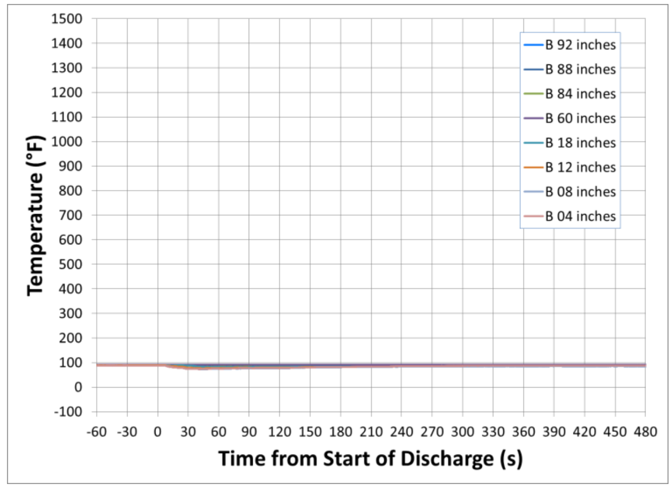
Pressure and Temperature in Pressurizer and Release Tanks



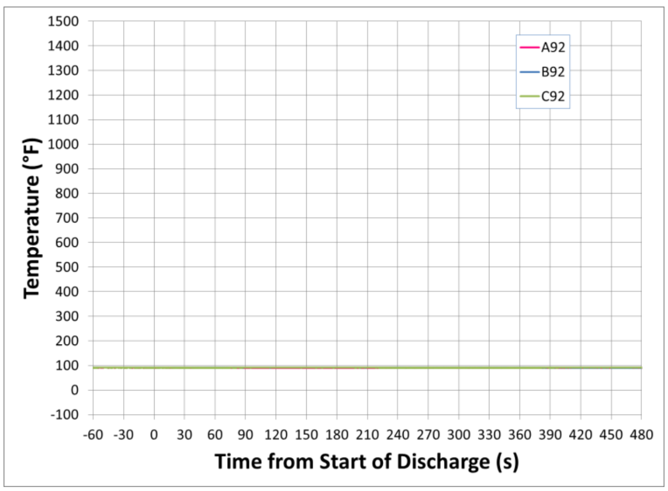
Refrigerant Release Rate



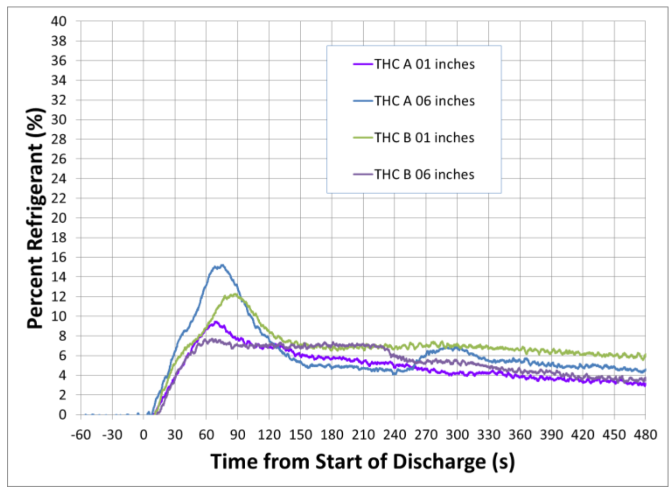
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

 Floor level view at 3 seconds after the start of the discharge	 Ceiling camera view at 56 seconds after the start of discharge.

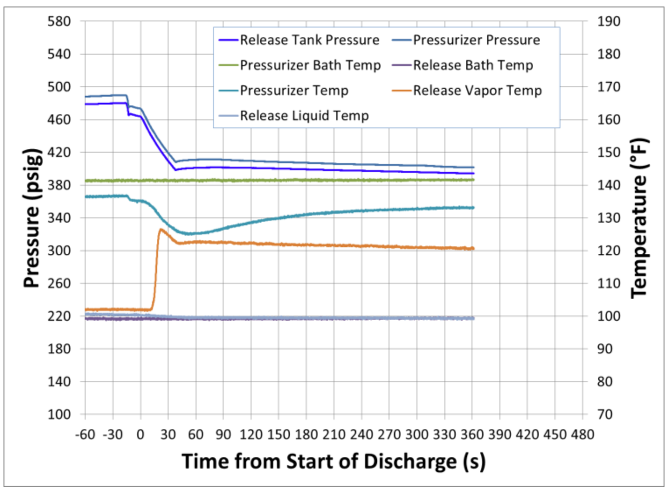
Figure 94 – Data from PTAC04

4.5.1.4.2. PTAC05:

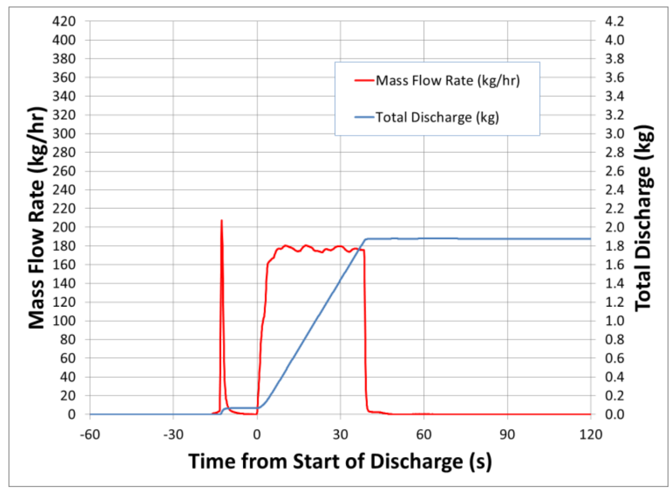
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Candle and Electric arc Ignition Time	Ignition Result
R-452B	50	1.82	Not Applicable	No ignition

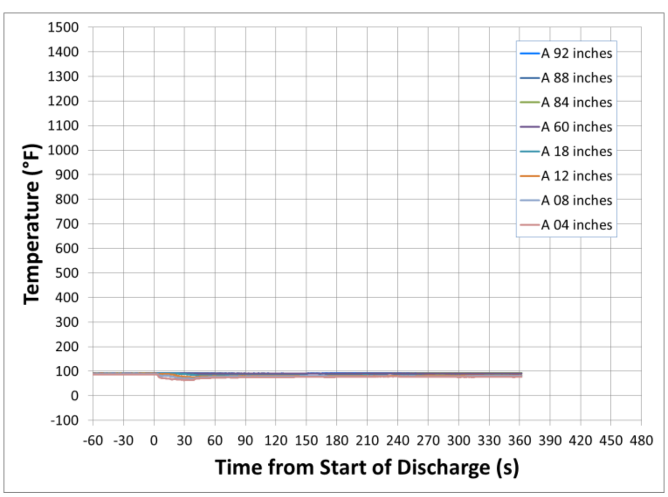
The purpose of this test was to determine the time that R-452B refrigerant concentration was at its maximum value. This data was then used to determine electric arc and candle ignition time in tests PTAC06 – PTAC08. Selected data from this test are shown in Figure 95.



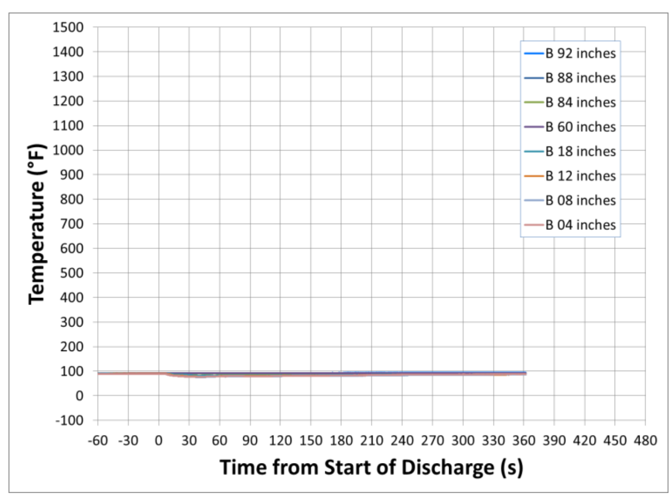
Pressure and Temperature in Pressurizer and Release Tanks



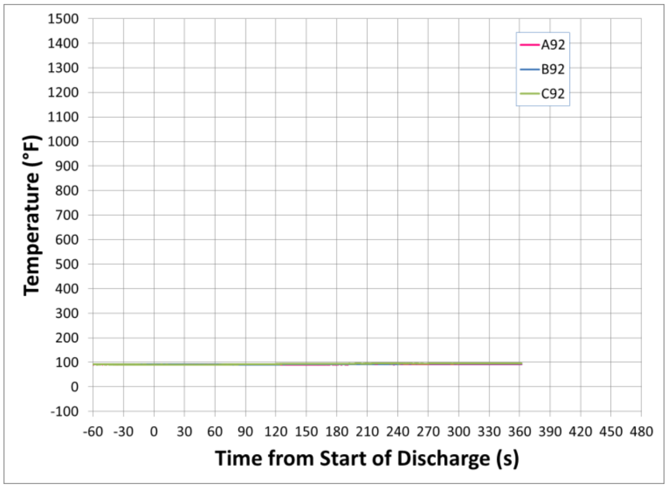
Refrigerant Release Rate



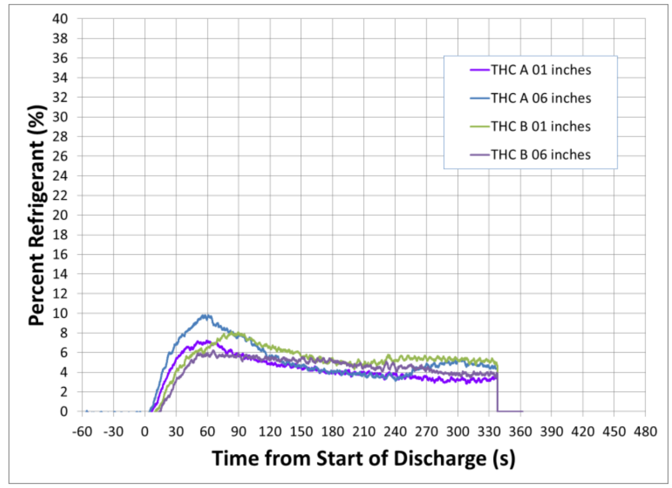
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

Floor level view at 3 seconds after the start of the discharge

Ceiling camera view at 56 seconds after the start of discharge (time of peak concentration at location A).

Figure 95 – Data from PTAC05

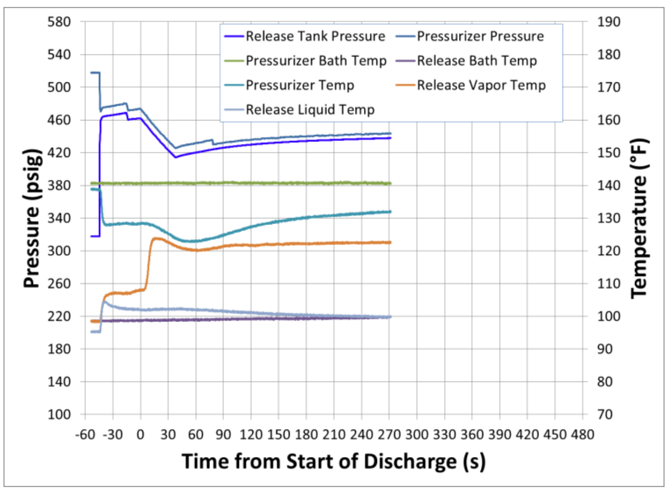
The initial time of 56 seconds for energizing the electric arcs and candles in the follow-on tests was based on the time to maximum concentration of these first two concentration build-up tests. R-32 had a slightly longer time to maximum concentration, it was noted that the discharge rate was about 10% lower than planned.

4.5.1.4.3. *PTAC06:*

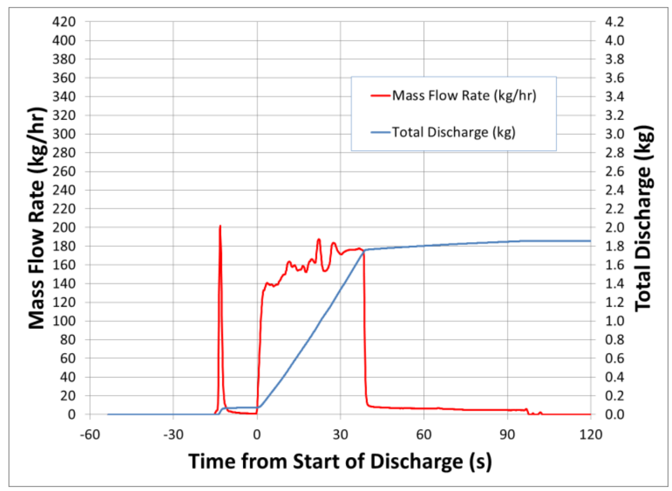
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Candle and Electric arc Ignition Time Target	Ignition Result
R-32	50	1.81	Start of Discharge + 56 seconds	No ignition

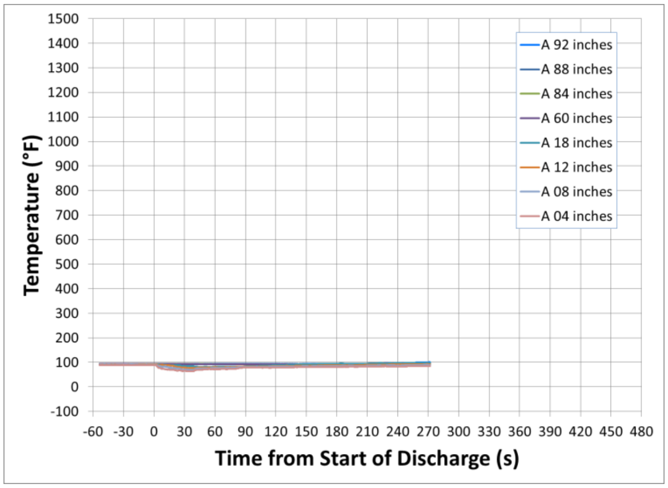
The purpose of this test was to attempt ignition of the discharged refrigerant at the time of maximum concentration determined in the PTAC04 test. Because of potential exposure to combustion products, ignition had to be delayed to 83 seconds to give time for the technician to exit the test area after completing the refrigerant discharge. Selected data from this test are shown in Figure 96.



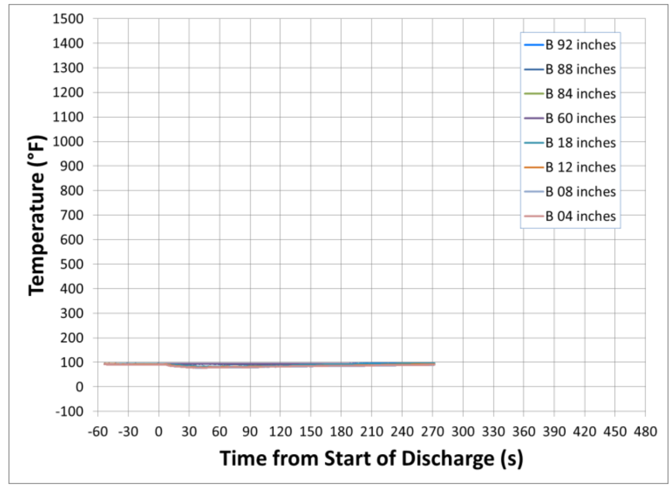
Pressure and Temperature in Pressurizer and Release Tanks



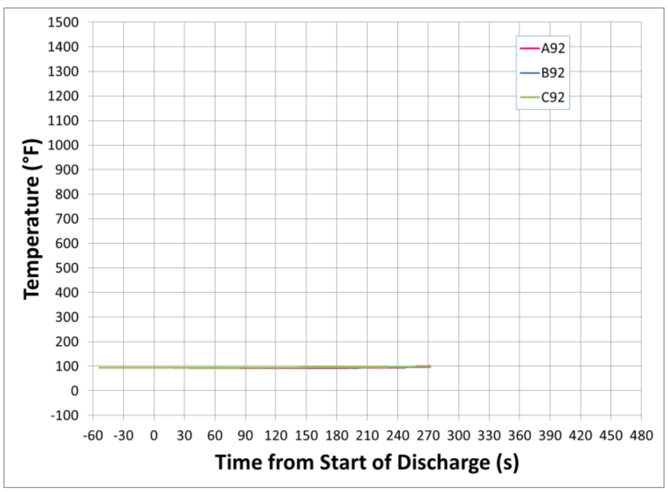
Refrigerant Release Rate



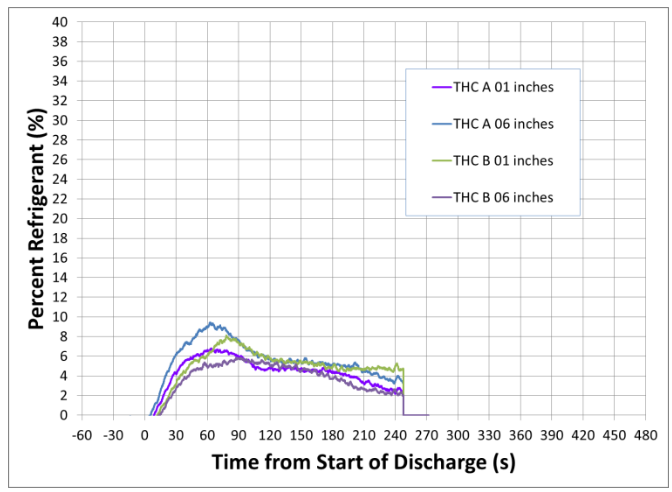
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

<table>
<tr>
<td>
Ceiling camera view at 3 seconds after the start of the discharge. The jet moving to the right was due to the discharge impinging on a vertical support of the grill face.</td>
<td>
Ceiling camera view at ignition of candles and electric arcs 83 seconds after the start of discharge. Ignition time was delayed by 27 seconds to give time for the technician to leave the test room.</td>
</tr>
</table>

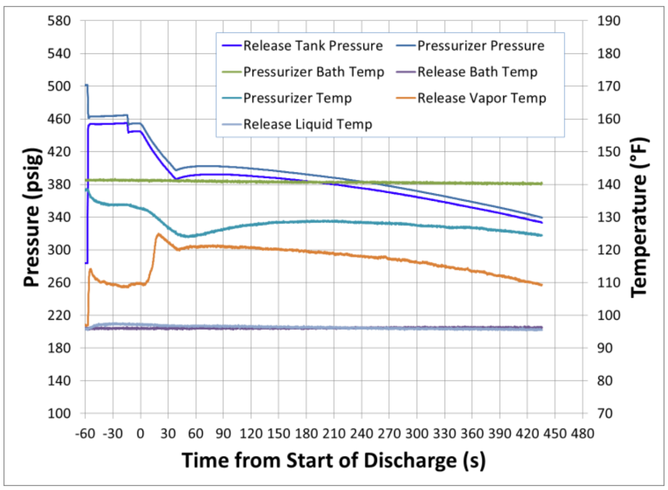
Figure 96 – Data from PTAC06

4.5.1.4.4. PTAC07:

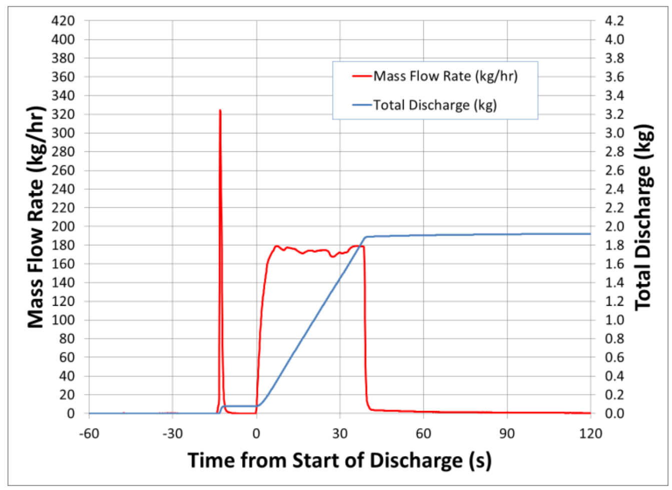
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Candle and Electric arc Ignition Time Target	Ignition Result
R-452B	50	1.82	Start of Discharge + 56 seconds	Small ignition (3 seconds)

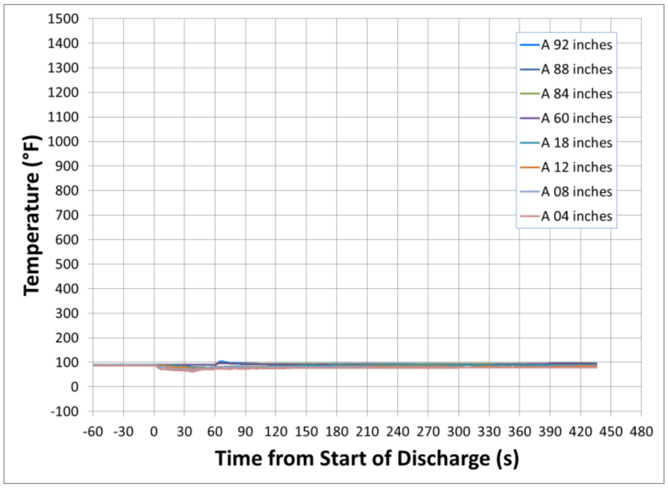
The purpose of this test was to attempt ignition of the discharged refrigerant at the time of maximum concentration determined in the PTAC04 test. Due to safety concerns ignition had to be delayed to 83 seconds to give time for the technician to exit the test area after completing the refrigerant discharge. Selected data from this test are shown in Figure 97.



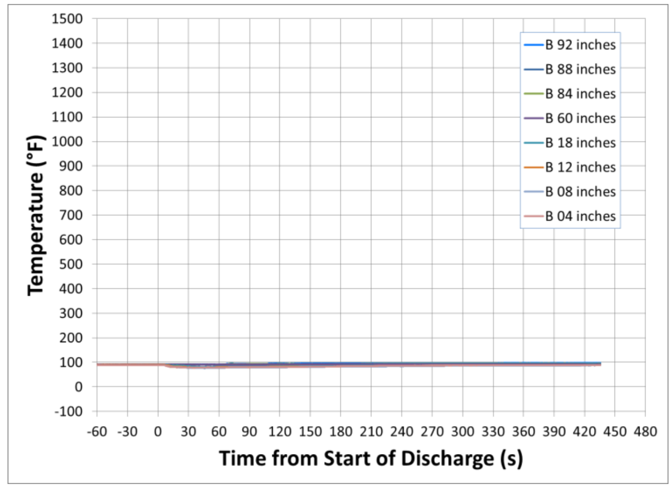
Pressure and Temperature in Pressurizer and Release Tanks



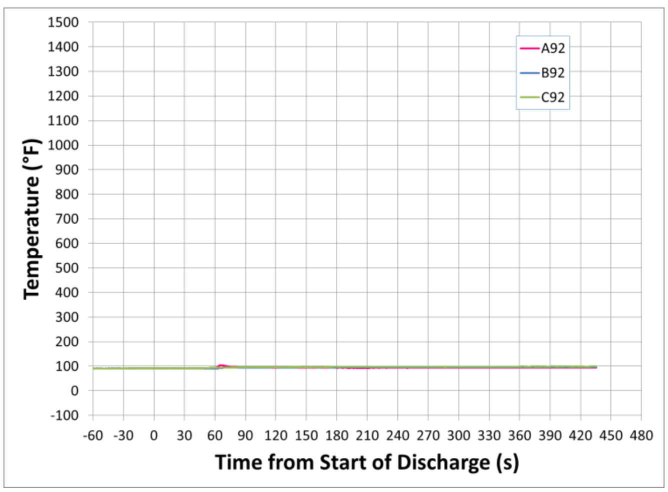
Refrigerant Release Rate



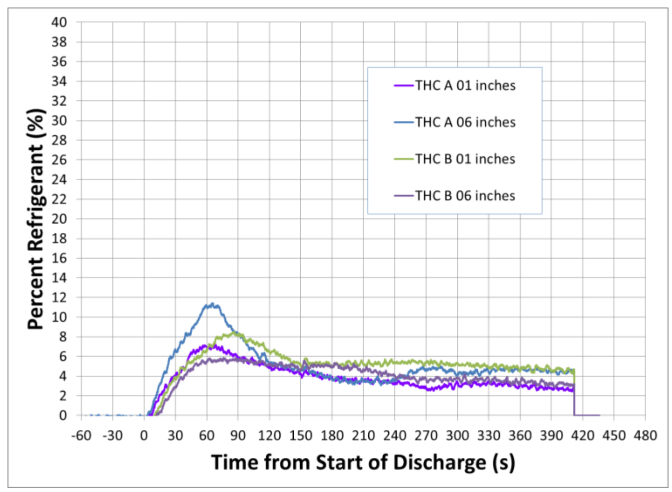
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

Ceiling camera view at 3 seconds after the start of the discharge. The jet moving to the right was due to the discharge impinging on a vertical support of the grill face.

Ceiling camera view at ignition of candles and electric arcs 57 seconds after the start of discharge.

A small refrigerant flame was observed near location A. The cheesecloth was not ignited. The total flaming time for the refrigerant flame was 3 seconds.

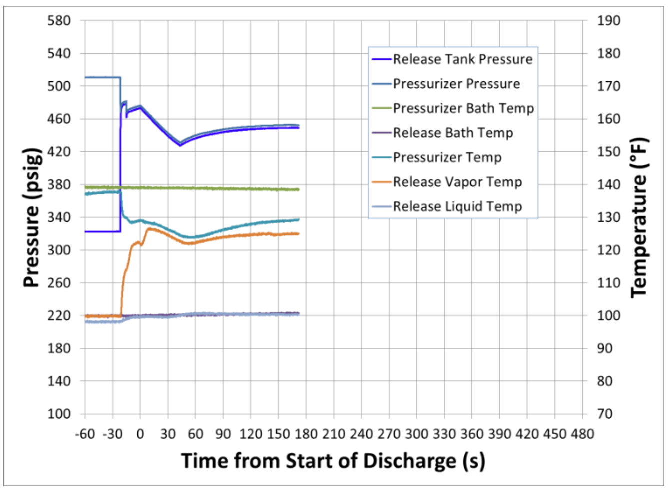
Figure 97 – Data from PTAC07

4.5.1.4.5. *PTAC08:*

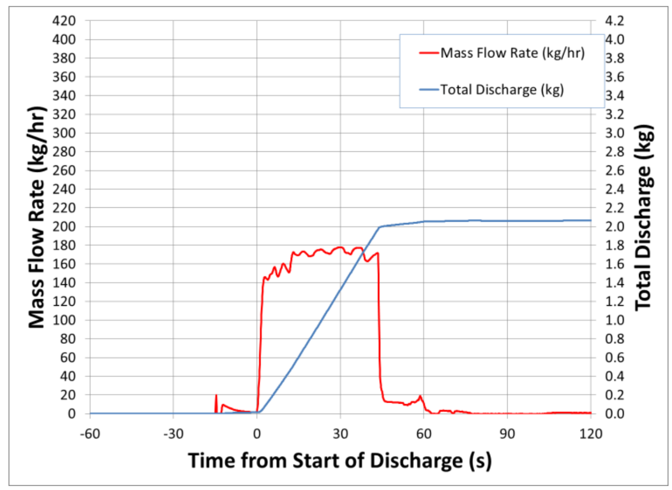
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Candle and Electric arc Ignition Time Target	Ignition Result
R-32	50	1.81	Start of Discharge + 20 seconds	No Ignition

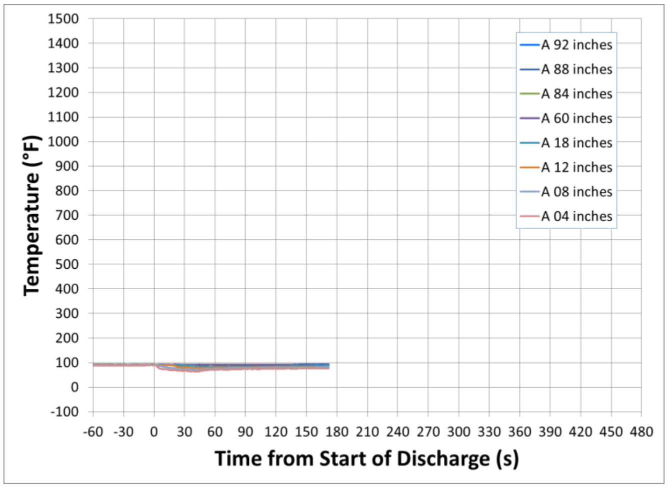
The purpose of this test was to attempt ignition of the discharged refrigerant at the time of maximum concentration determined in the PTAC04 test. Because of potential exposure to combustion products, ignition had to be delayed to 74 seconds to give time for the technician to exit the test area after completing the refrigerant discharge. Selected data from this test are shown in Figure 98.



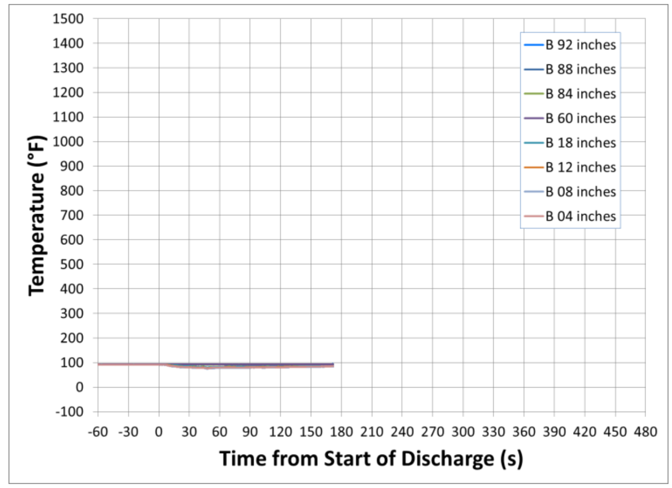
Pressure and Temperature in Pressurizer and Release Tanks



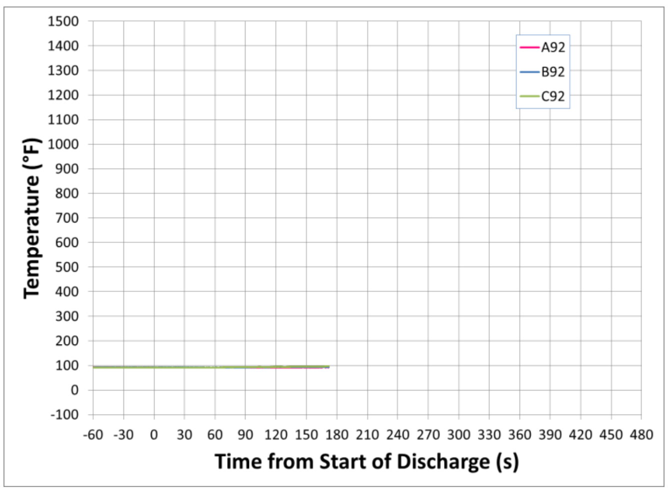
Refrigerant Release Rate



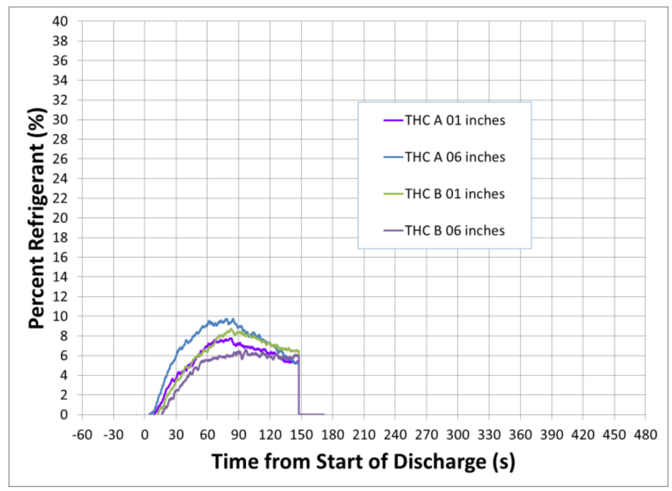
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

 Ceiling camera view at 3 seconds after the start of the discharge. The jet moving to the right was due to the discharge impinging on a vertical support of the grill face.	 Ceiling camera view at ignition of candles and electric arcs 74 seconds after the start of discharge. Ignition time was delayed by 54 seconds to give time for the technician to leave the test room after closing the manual discharge valves.

Figure 98 – Data from PTAC08

4.5.1.4.6. PTAC09:

The test parameters for this test were as follows:

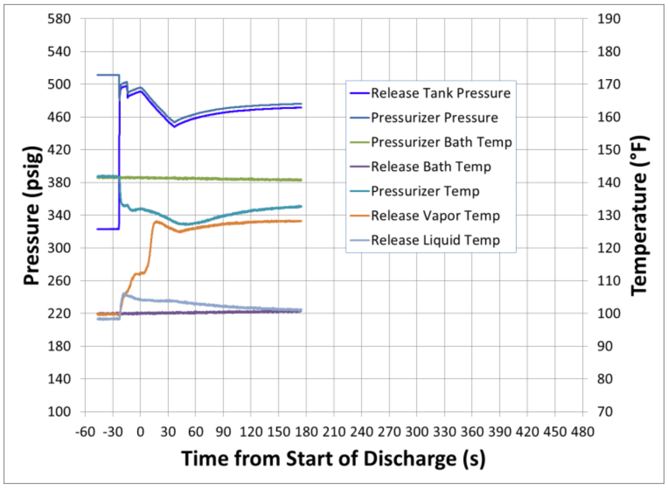
Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Candle and Electric arc Ignition Time Target	Ignition Result
R-32	50	1.81	Pre-lit Candles Electric arc ignited after technician left the area	No Ignition

The purpose of this test was to attempt ignition of the discharged refrigerant with the candles ignited before the start of the discharge. Beginning with this test and the remainder of this series, the discharge tube was moved to the left side of the coil face, angled toward the floor, and placed such that the discharge did not impact a vertical support in the grill face. Supplementary pre-lit candles were added at location A (1, 12, 24, and 36 inches). An additional electric arc was added at location A at 24 inches above the floor. Selected data from this test are shown in Figure 99.

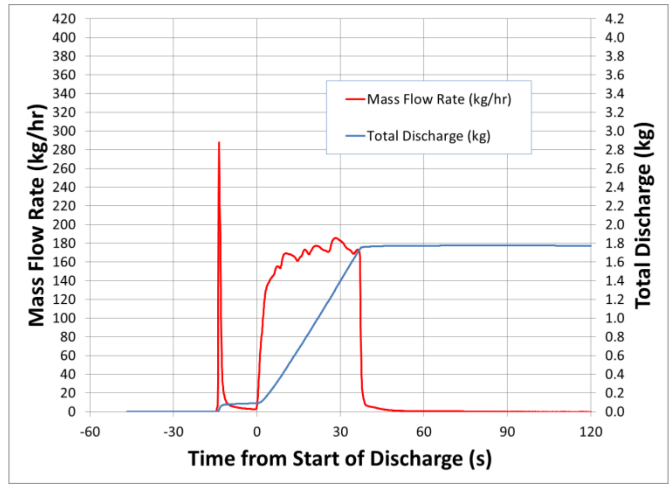
The locations of the instrumentation and ignition sources were located in clusters at locations A, B, and C. The locations relative to the front and right walls are shown in Table 25. These locations apply to tests PTAC09 and PTAC10.

Table 25 – Location of Instrumentation and Ignition Sources

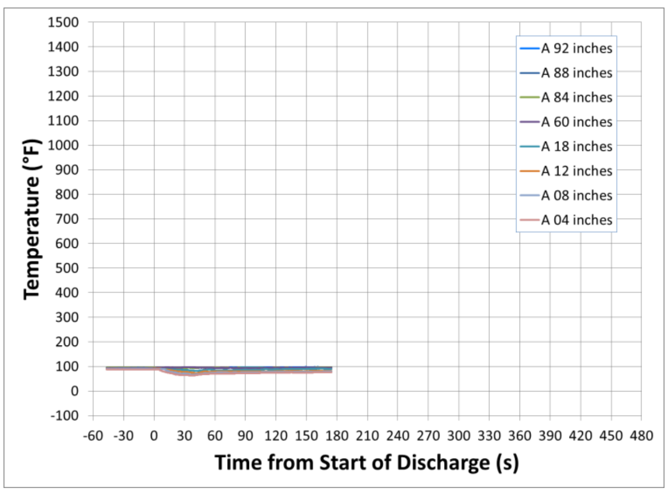
Item	Location	Number	Height above Floor (in.)	Distance from front wall (ft.)	Distance from right wall (ft.)
Refrigerant sensor	A	2	1, 6	1.5	6.5
	B	1	1, 6	8	10
Thermocouples	A	8	4, 8, 12, 18, 60, 84, 88, 92	1.5	6.5
	B	8	4, 8, 12, 18, 60, 84, 88, 92	8	10
	C	8	4, 8, 12, 18, 60, 84, 88, 92	14	6.5
Pilot flame	A	1	1, 12, 24,36	1.5	6.5
	B	1	1	8	10
	C	1	1	14	6.5
Electric arc	Side of PTAC	3	1, 6, 24	2 inches	8
	Side of Bed	1	6	5	2 inches



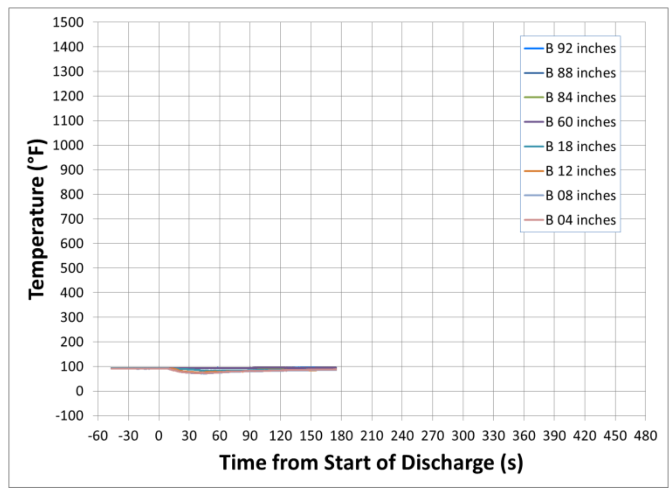
Pressure and Temperature in Pressurizer and Release Tanks



Refrigerant Release Rate



Temperature at Location A



Temperature at Location B

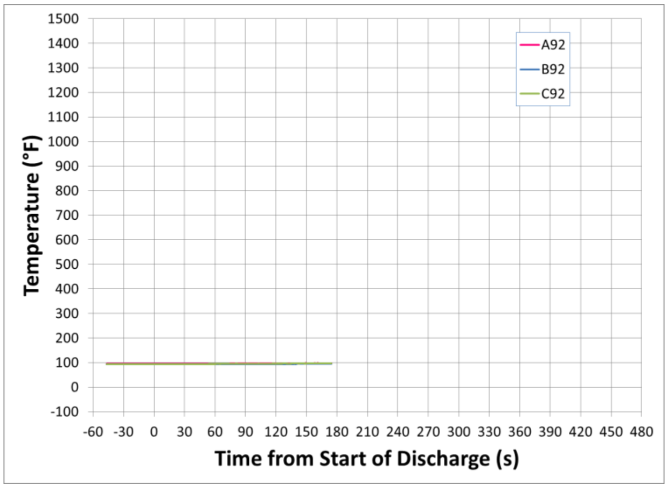
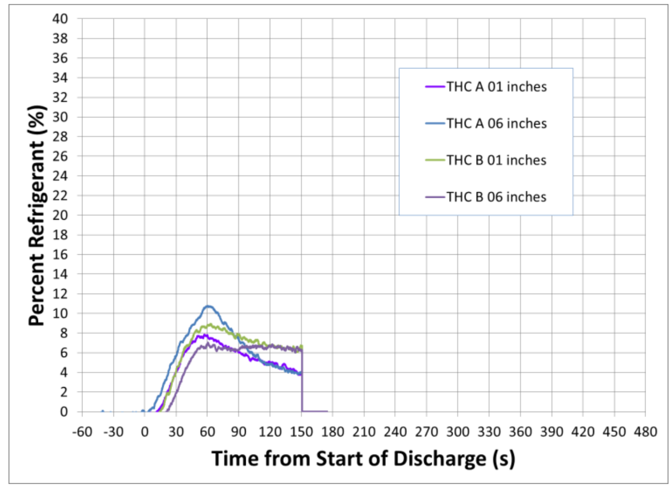
	
Temperature at 92 in. height above the floor	Refrigerant Concentration
	
Floor camera view showing additional candles at location A and an additional electric arc at 24 inches.	Floor camera view at 51 seconds after the start of the discharge. The discharge was completed 38 seconds after the flow had started. The electric arcs were activated 3 seconds before this frame. The 24 inch electric arc shows some flaring, but there was no flaring at any other location. The candle at 1 inch height is nearly obscured by the mist.

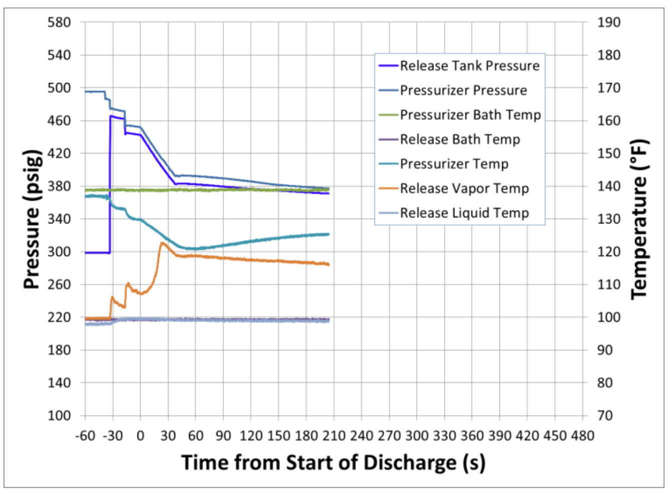
Figure 99 – Data from PTAC09

4.5.1.4.7. *PTAC10:*

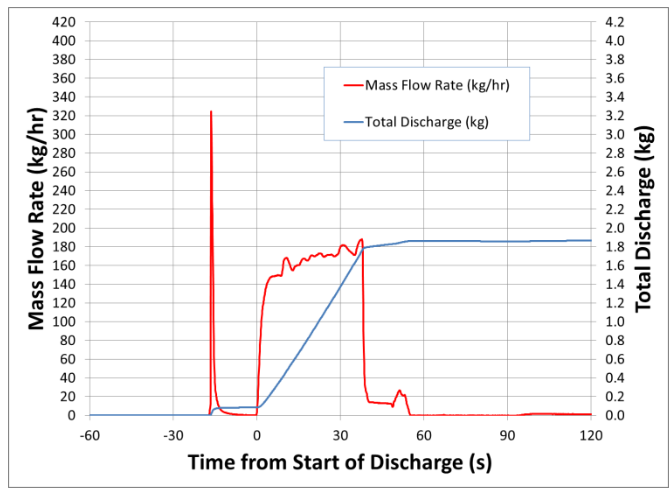
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Candle and Electric arc Ignition Time Target	Ignition Result
R-452B	50	1.82	Pre-lit Candles Electric arc ignited after technician left the area	No Ignition

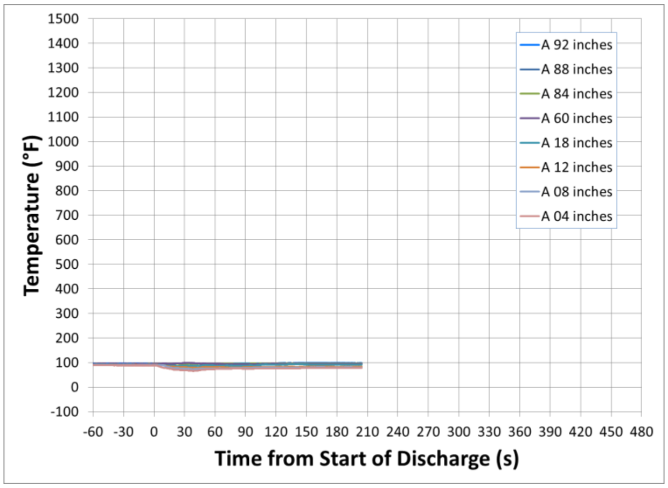
The purpose of this test was to attempt ignition of the discharged refrigerant with the candles and electric arcs initiated before the beginning of the discharge. The discharge tube was located at the left side of the coil face, angled toward the floor, and placed such that the discharge did not impact a vertical support in the grill face. Selected data from this test are shown in Figure 100.



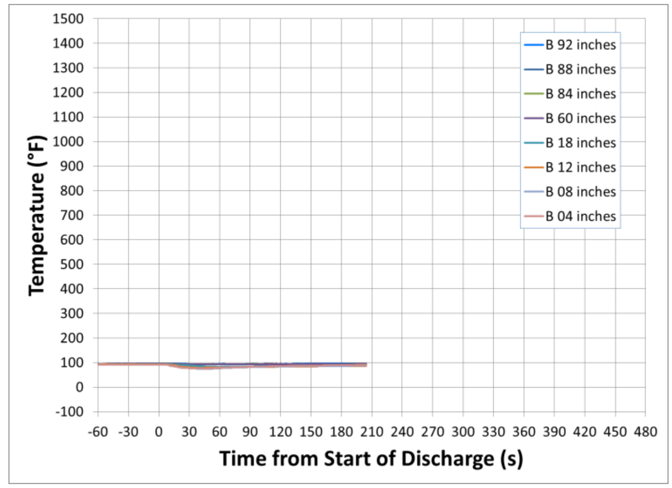
Pressure and Temperature in Pressurizer and Release Tanks



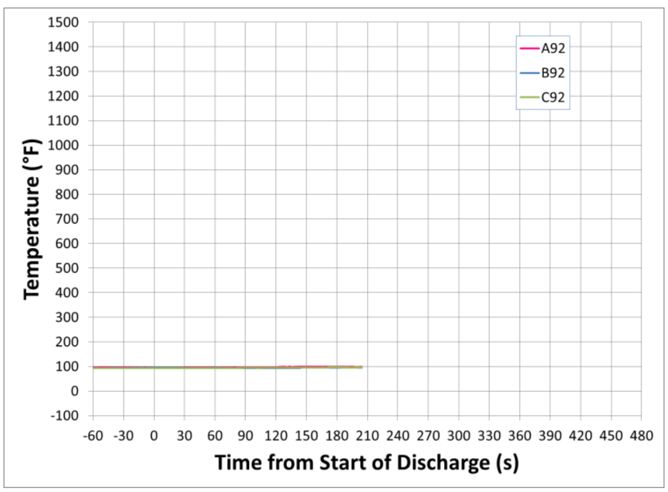
Refrigerant Release Rate



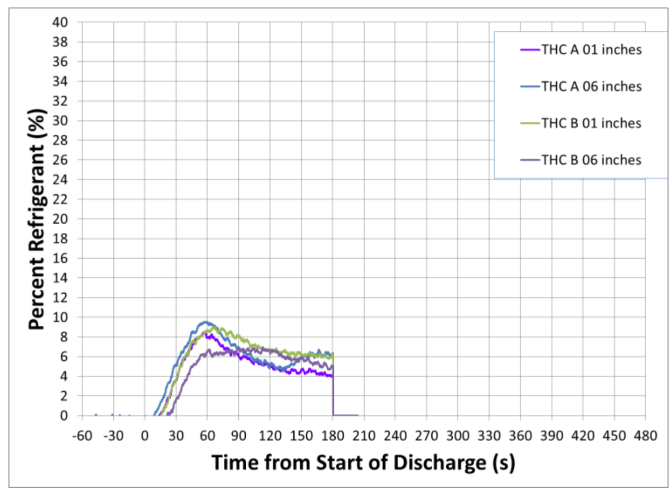
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

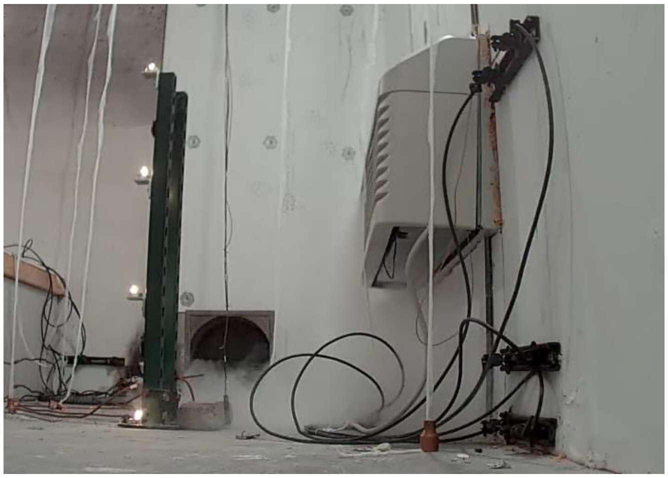
	
Floor camera view showing additional candles at location A and an additional electric arc at 24 inches. This frame is taken 2 seconds after the start of the discharge.	Floor camera view at 60 seconds after the start of the discharge and the technician had left the area. The electric arcs were started 19 seconds before this frame. All candles and electric arcs showed signs of flaring during the period.

Figure 100 – Data from PTAC10

4.5.1.4.8. PTAC11:

The test parameters for this test were as follows:

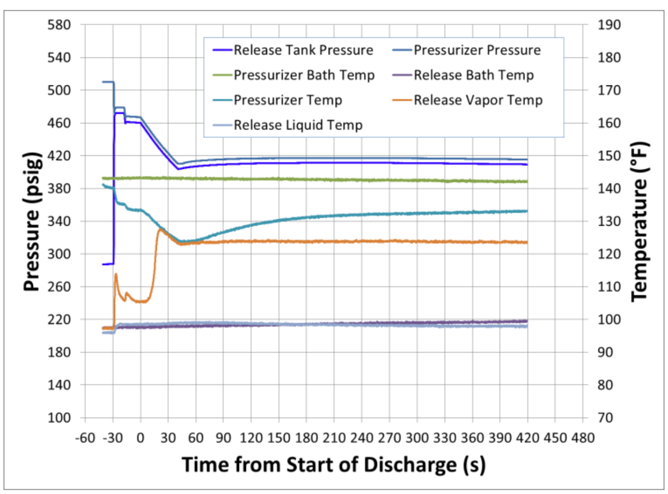
Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Candle and Electric arc Ignition Time Target	Ignition Result
R-452B	50	1.82	Not Applicable	No Ignition

In tests PTAC11, PTAC12, and MPTAC01, the PTAC unit was moved to the minimum distance (3 inches) from the side wall. No ignition was attempted in this test as the purpose was to compare the resulting refrigerant concentrations with the earlier R-452B tests. The refrigerant sensors were relocated as shown in Figure 88. Selected data from this test are shown in Figure 101.

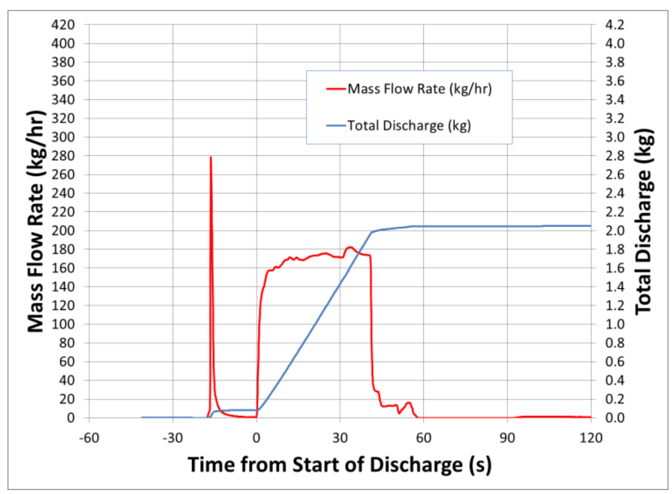
The locations of the instrumentation were located in clusters at locations A, and B. The locations relative to the front and right walls are shown in Table 26. These locations apply to tests PTAC09 and PTAC10.

Table 26 – Location of Instrumentation and Ignition Sources

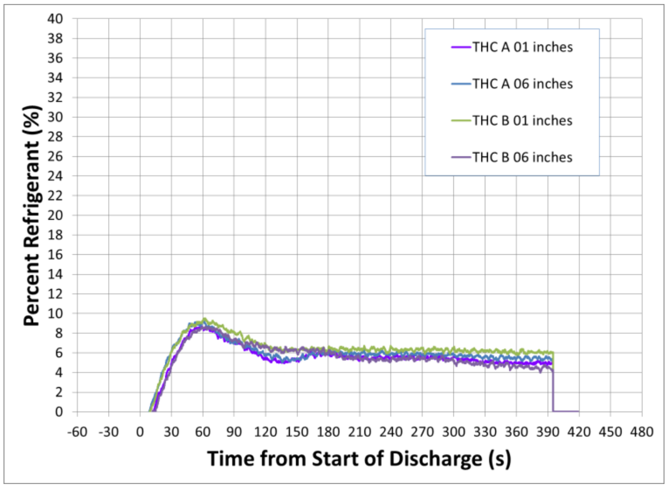
Item	Location	Number	Height above Floor (in.)	Distance from front wall (ft.)	Distance from right wall (ft.)
Refrigerant sensor	A	2	1, 6	2	2
	B	2	1, 6	3	6.5



Pressure and Temperature in Pressurizer and Release Tanks



Refrigerant Release Rate



Refrigerant Concentration PTAC11

Ceiling camera view 10 seconds after the beginning of the discharge. While not apparent in a still frame, the video shows that discharge location near the corner of the room is directing the mist away from that corner and drawing in fresh air from above the bed.

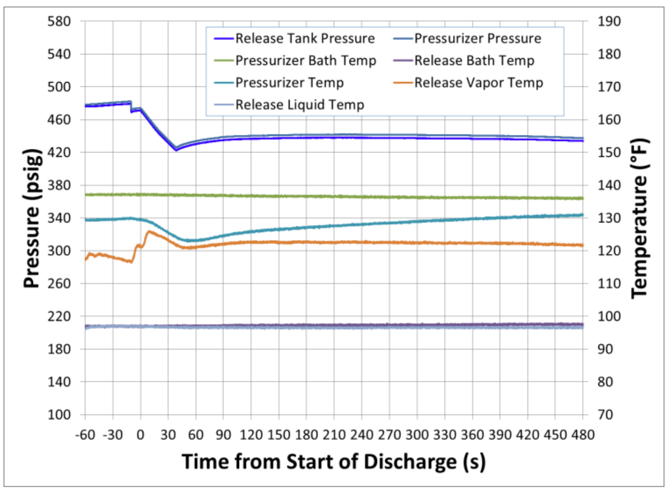
Figure 101 – Data from PTAC11

4.5.1.4.9. *PTAC12:*

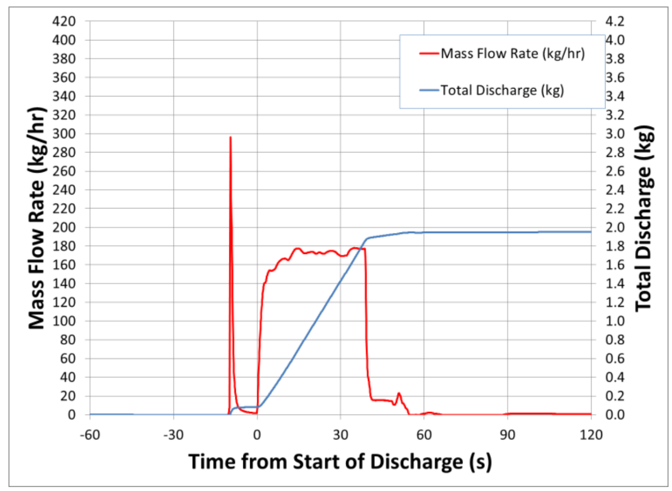
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Candle and Electric arc Ignition Time Target	Ignition Result
R-32	50	1.81	Not Applicable	No Ignition

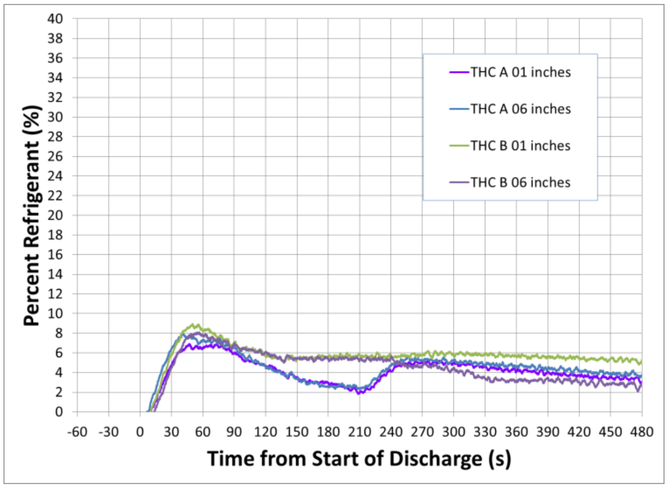
The PTAC unit was located at the minimum distance (3 inches) from the side wall. No ignition was attempted in this test as the purpose was to compare the resulting refrigerant concentrations with the earlier R-32 tests. The refrigerant sensors were relocated as shown in Figure 88. Selected data from this test are shown in Figure 102.



Pressure and Temperature in Pressurizer and Release Tanks

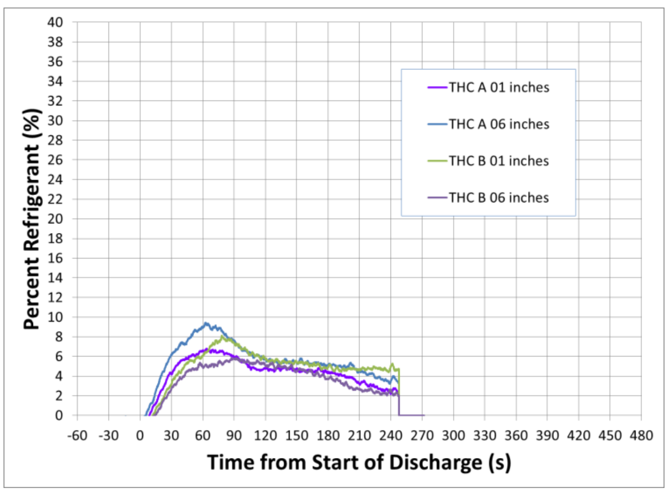


Refrigerant Release Rate

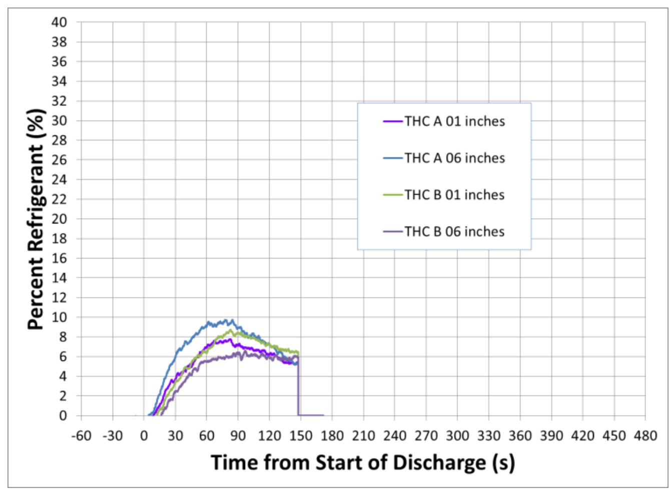


Refrigerant Concentration PTAC11

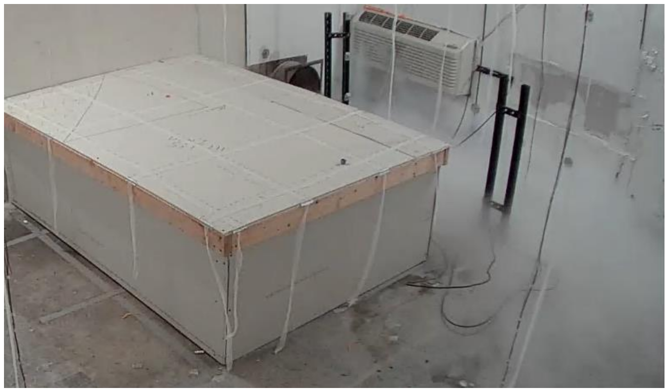
The concentrations for the previous R-32 tests are included below. Note that the peak concentrations in PTAC12 are less than the previous tests.



Refrigerant Concentration PTAC06



Refrigerant Concentration PTAC08



Ceiling camera view 10 seconds after the beginning of the discharge. While not apparent in a still frame, the video shows that the discharge location near the corner of the room is sweeping the mist away from that corner and entraining in fresh air from above the bed.

Figure 102 – Data from PTAC12

4.5.1.4.10. *MPTAC01:*

The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Candle and Electric arc Ignition Time Target	Ignition Result
R-32	50	1.81	No Candles; Electric arcs ignited before discharge	Ignition

This modified PTAC test was designed to place electric arcs in the discharge stream directly in front of the discharge tube embedded in the coil face. One opinion that had been expressed was that it is hard to have sustained combustion of low burning velocity refrigerants when the velocity of the surrounding air is many times the burning velocity. The PTAC tests had been completed and the equipment remained in place. This additional test was conducted to see what would happen when an ignition source is in the high velocity refrigerant stream where the refrigerant concentration is well above the LFL. Figure 103 shows a close-up of this arrangement. The refrigerant sampling tubes were placed at 12, 16, 20, and 24 inches above the floor. The electric arcs were placed at 14, 18, 22, and 26 inches above the floor. Because of potential interference from the electric arcs, the thermocouple trees were placed as shown in Figure 104.

This test resulted in a large fire event that was complicated by a failure of the refrigerant mass flow control valve to close. An unsuccessful attempt was made to stop the test 30 seconds after the start of discharge. This failure resulted in 1.1 more kilograms of release than planned. It is suspected that the vicinity of the electric arc discharges in close proximity to the refrigerant discharge tube (copper) resulted in electronic interference strong enough to disrupt the mass flow control system. Refrigerant flow was finally stopped by closing the manual shutoff valves.

The locations of the instrumentation, and ignition sources were located in clusters at locations A, B, and C and a separate location for the electric arc tower. The locations relative to the front and right walls are shown in Table 27.

Table 27 – Location of Instrumentation and Ignition Sources

Item	Location	Number	Height above Floor (in.)	Distance from front wall (ft.)	Distance from right wall (ft.)
Refrigerant sensor	Electric arc Tower	4	12, 16, 20, 24	1	0.5
Thermocouples	A	8	4, 8, 12, 18, 60, 84, 88, 92	1.5	6.5
	B	8	4, 8, 12, 18, 60, 84, 88, 92	8	10
	C	8	4, 8, 12, 18, 60, 84, 88, 92	14	6.5
Electric arc	Electric arc Tower	4	14, 18, 22, 26	1	0.5

Figure 103 – Electric arcs and refrigerant sampling tubes immediately in front of discharge location

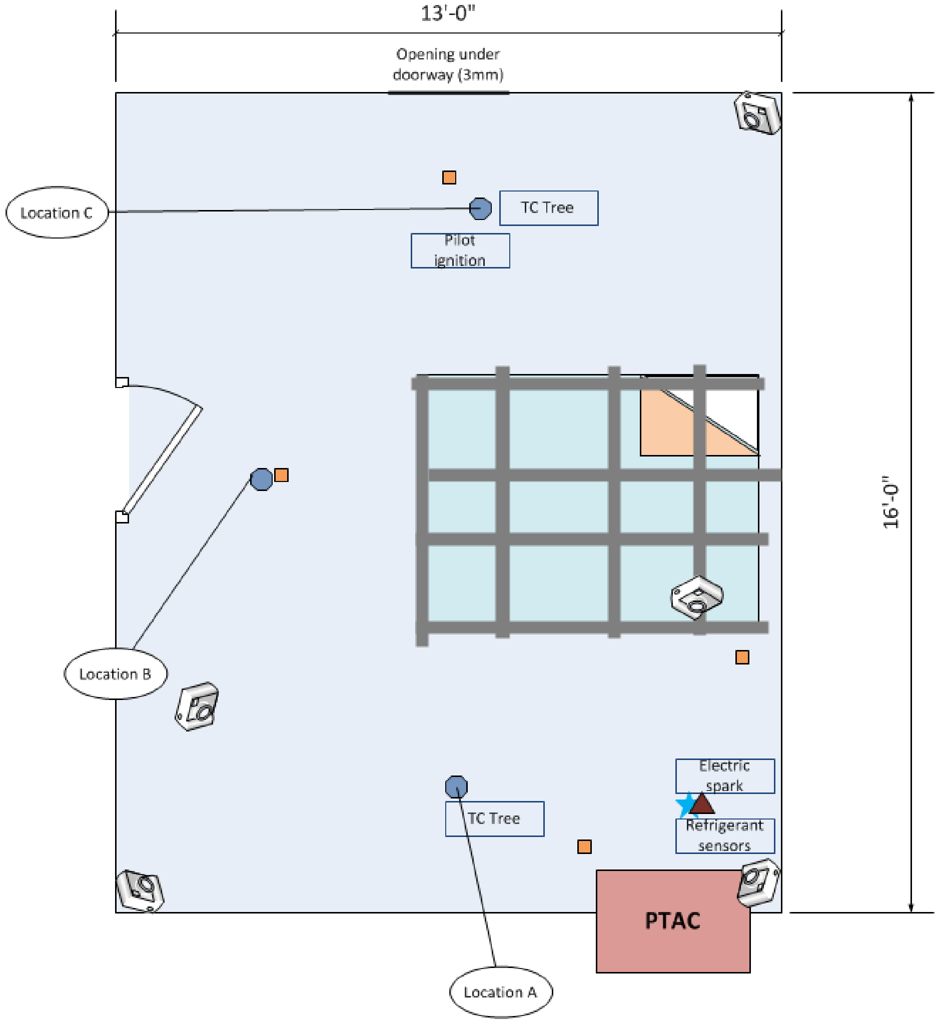
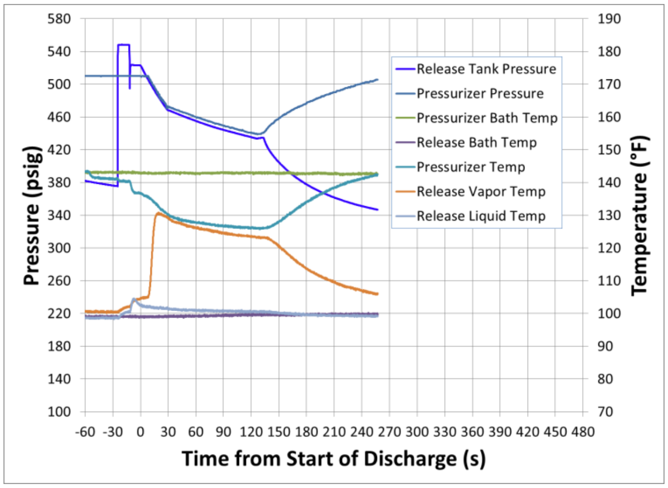
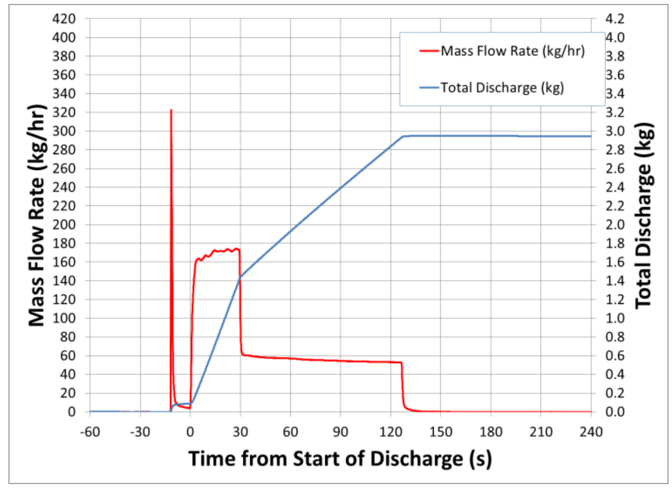


Figure 104 – Instrumentation for MPTAC01

Selected data from this test are shown in Figure 105.

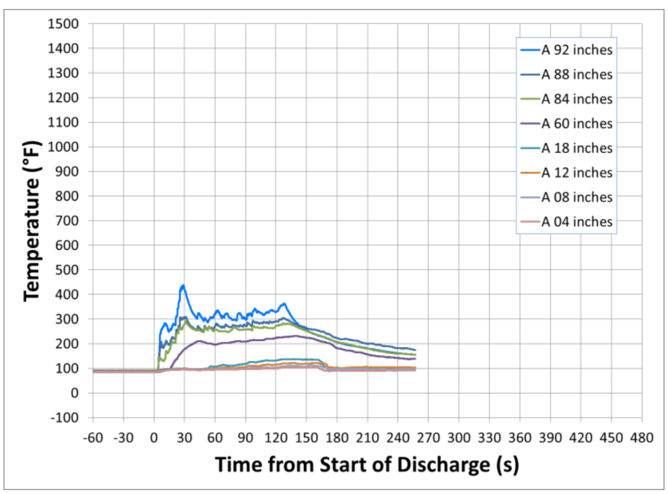


Pressure and Temperature in Pressurizer and Release Tanks

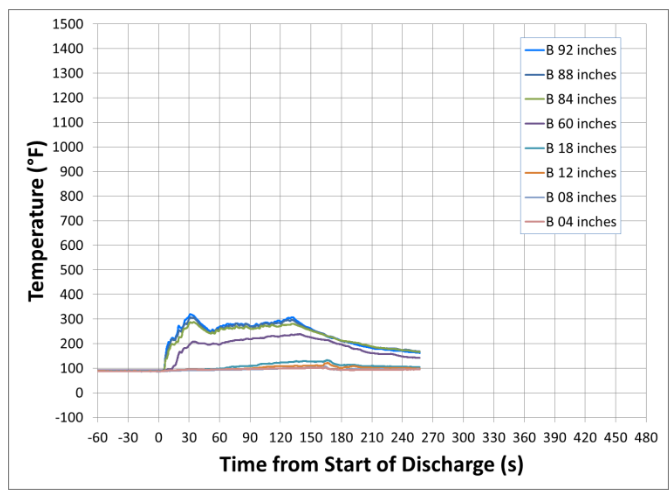


Refrigerant Release Rate

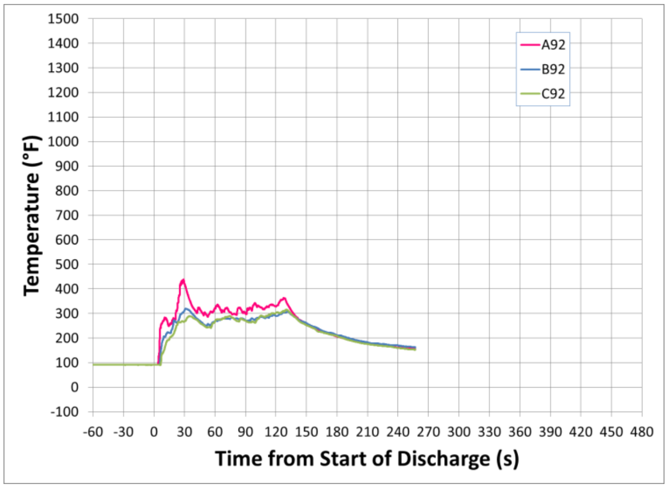
The graph shows that the refrigerant control valve did not completely close



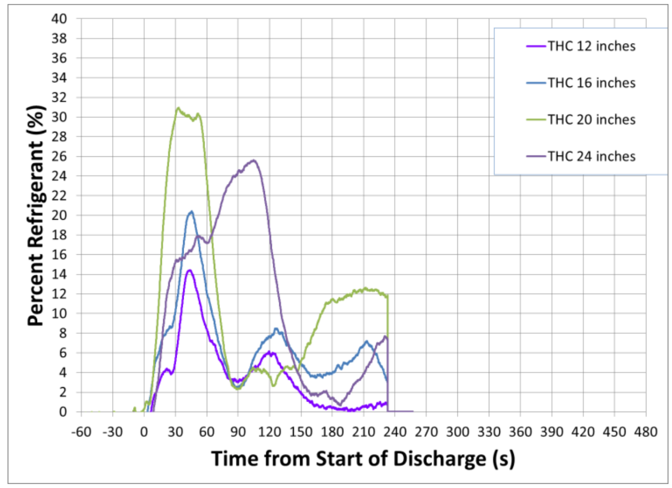
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

Floor camera view 7 seconds after start of discharge

Floor camera view 30 seconds after start of discharge

Camera in front of PTAC showing flames extending downward from the electric arcs due to the force of the discharge jet. (20 seconds after start of discharge)

Camera in front of PTAC 30 seconds after start of discharge showing the start of one large flare. Six frames later (0.2 seconds), this camera view was washed out due to the size of the flame.

Figure 105 – Data from MPTAC01

4.5.2. Reach-in Cooler Scenario

The reach-in cooler scenario involved a product display refrigerator located in a convenience store layout. The test setup for the reach-in cooler is shown in Figure 106. The convenience store dimensions were 30 x 30 x 8-ft. high. Objects representing shelves were located in the test area.

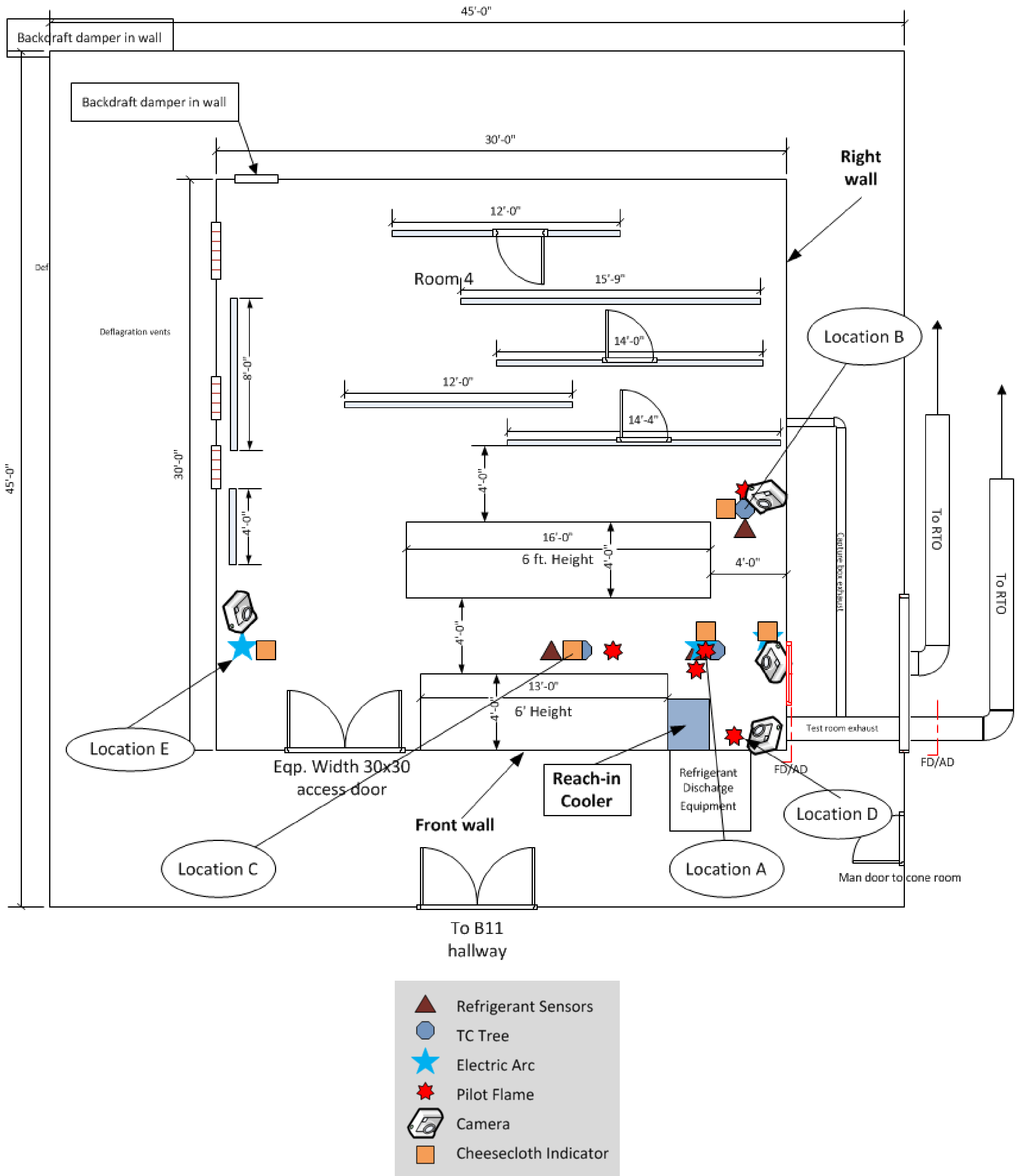


Figure 106 – Reach-in Cooler Test Setup

The reach-in cooler had outer dimensions of 27.4 (w) x 32.5 (d) x 79.6 (h) inches with an internal volume of 21 cu. ft.

The locations of the instrumentation, and ignition sources were located in clusters at locations A, B, C, D, and E. The locations relative to the front and right walls are shown in Table 21.

Table 28 – Location of Instrumentation and Ignition Sources

Item	Location	Number	Height above Floor (in.)	Distance from front wall (ft.)	Distance from right wall (ft.)
Refrigerant sensor	A	2	1, 6	6	5.5
	B	1	1	12	2
	C	1	1	5	13
Thermocouples	A	8	4, 8, 12, 18, 60, 84, 88, 92	6	5.5
	B	8	4, 8, 12, 18, 60, 84, 88, 92	12	2
	C	8	4, 8, 12, 18, 60, 84, 88, 92	5	13
Pilot flame	A		1	6	5.5
	B		1	12	2
	C		1	5	13
	D		1	1	3.5
Electric Arc ignition source	A	2	1, 6	6	5.5
	B	1	1	12	2
	C	1	1	5	13
	E	1	1	5	29.5

4.5.2.1. Refrigerant Release

Initially, the planned refrigerant release quantities were:

- 500 g (current limit for class 2 flammable refrigerant in UL 471 edition 10 including revisions through November 2014), and
- $13\ m^3 \times LFL\ \frac{kg}{m^3}$ (proposed charge limit per IEC 60335-2-89, as a revision to the current limit of 150 g for any flammable refrigerant found in IEC 60335-2-89:2010 Edition 2.2[12]).

The refrigerant release rate was set to 10 g/s through a ¼ in. copper tubing leading in to the top compartment of the reach-in cooler. The length of the tube was approximately 3 meters and was attached to a 1 by ¼ inch reducer at the exit of the mass flow control valve. The refrigerant release rate was selected so as not to blow the reach-in cooler door open during the release. The bottom door was connected to a pneumatic device to remotely open the door when the refrigerant was completely released into the cabinet. The opening of the door was constrained to open partially.

[12] International Electrotechnical Commission (IEC), 60335-2-89:2010 +AMD1:2012 +AMD2:2015 Edition 2.2

The refrigerant release quantities were reduced after the tests with 500g of refrigerant release resulted in its ignition and flaming in the room. A test matrix of refrigerant release quantities are shown in Table 29.

Table 29 – Reach in Cooler Experimental Matrix

Test Number	Refrigerant	Release Quantity (g)
Cooler01	R-455A	500g
Cooler02	R-457A	500g
Cooler03 [1]	R-457A	300g
Cooler04 [1]	R-457A	400g

Note 1: After discussions of the results from tests 1 and 2 with the AHRTI PMS, it was decided not to conduct tests with refrigerant release quantity equivalent to 13 times the LFL (which would be approximately 5.4 kg (13*0.415 kg/m^3) for R-455A and 2.7 kg (13*0.211 kg/m^3) for R-457A, but to investigate refrigerant release amounts at which ignition does not take place. R-457A refrigerant was selected for the additional tests since R-457A resulted in more energetic flaming.

4.5.2.2. Test Procedure

The following procedure was used to initiate each test:

1. Confirm pressure and release refrigerant tank pressure and temperatures.
2. Confirm the test room temperature and humidity
3. Light the candles and turn off the lab HVAC and humidity systems.
4. Initiate data acquisition and video capture 1 minute prior to discharging refrigerant.
5. Develop vacuum (less than 1mm Hg) in piping connecting the pressure and release tanks as well between the release tank and flow meter.
6. Open the valve between the pressure and release tanks, and hold for 5 seconds; open the valve between release tank and the flow meter and hold for 5 seconds.
7. Energize the solenoid valves to enable refrigerant discharge.
8. Open the control valve to initiate refrigerant discharge through the mass flow meter.
9. Open the bottom reach-in cooler door when the planned refrigerant quantity was released.

After each test, the test facility was exhausted through UL's smoke abatement system, and the conditions in the facility were monitored with open path gas FT-IR. Staff re-entered the test facility for the only after the gas FT-IR indicated normal ambient conditions.

4.5.2.3. Summary of Findings – Reach-in Cooler Tests

The results from the reach-in cooler tests showed that ignition of the refrigerant may occur with an A2L refrigerant release quantity greater than 300g. The fire spread indicates that walls and corners in proximity of the reach-in cooler facilitate higher concentrations of refrigerants.

In those cases where ignition occurred, the highest temperatures attained were near the floor level. Figure 107 shows that there was no ignition with a release of 300 grams of R-457A. The 300 gram test showed some flaring of the candles due to the presence of refrigerant, but there was no visible spread of flame into the surrounding air. Temperatures from the events increased with increasing charge size. R-455A with a release of 600 grams showed lower temperatures than R-457A with a release mass of 500 grams.

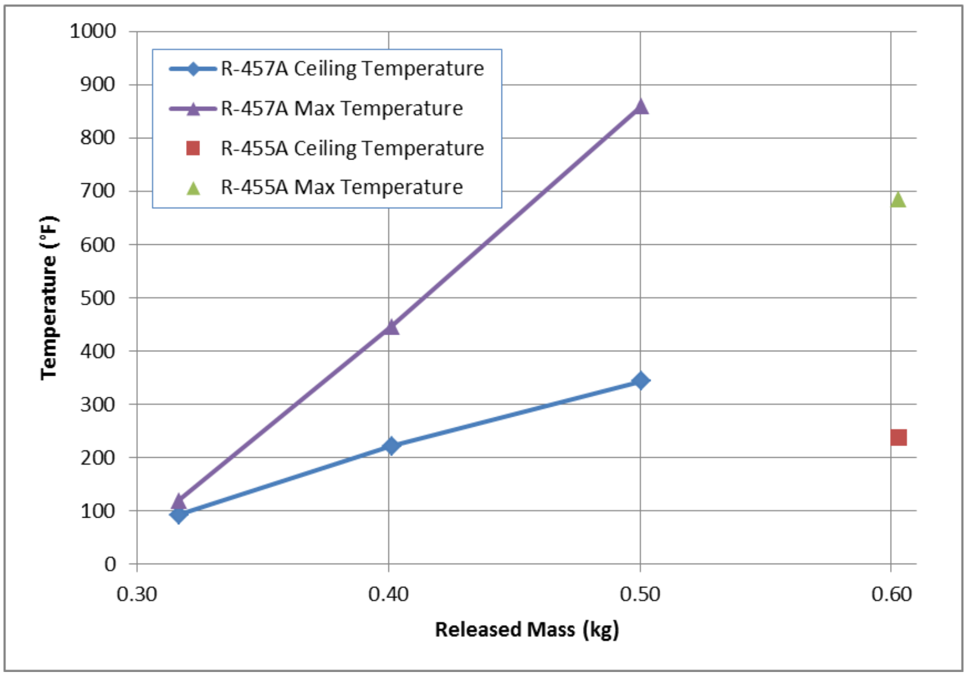


Figure 107 – Maximum Temperatures and Ceiling Temperatures

In tests 1, 2, and 4 ignition occurred within 2 to 3 seconds after the reach-in cooler door was opened. In contrast to this observation, the deconvoluted refrigerant concentration data showed values well below the LFL. The reason for this is the sensor time delay and the slug flow assumption of deconvolution that was discussed in Task 1. The transport delay time of 20 seconds was much longer than the 2-3 seconds to ignition and nearly the same as the total flaming time of 9 to 30 seconds. The resultant mixing of high and low concentrations in the sample line during transport averaged the peak refrigerant concentration to values below the LFL when the deconvolution algorithm was applied to the sensor data.

4.5.2.4. Results

A summary of test results are presented in Table 30.

Table 30 – Reach-in Cooler Test Summary

Test Number	Refrigerant	Planned Release Quantity (kg)	Max Pressure (mm Hg)	Max Temperature and Location (°F) /Location	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	Measured Release Quantity (kg)	Result
Cooler01	R-455A	0.50	0.01	685 / A12	274	238	0.60	Ignition
Cooler02	R-457A	0.50	0.05	859 / A04	437	343	0.50	Ignition
Cooler03	R-457A	0.30	0.01	119 / B12	94	93	0.32	No Ignition
Cooler04	R-457A	0.40	0.02	446 / A04	281	222	0.40	Ignition

The test results for the tests are presented herein.

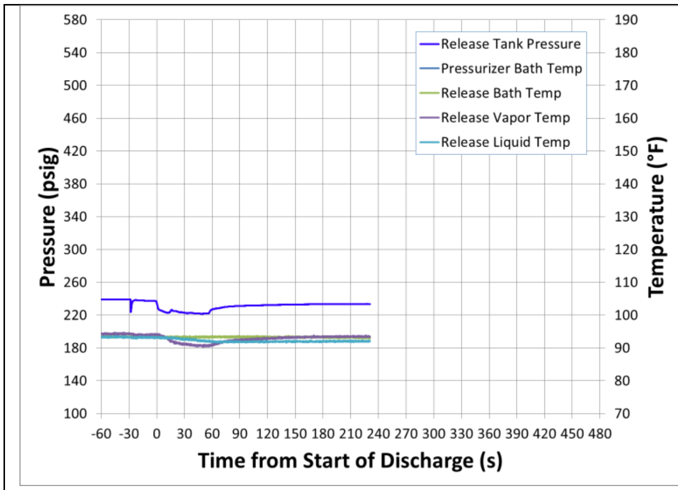
4.5.2.4.1. *Cooler01*

The test parameters for this test were as follows:

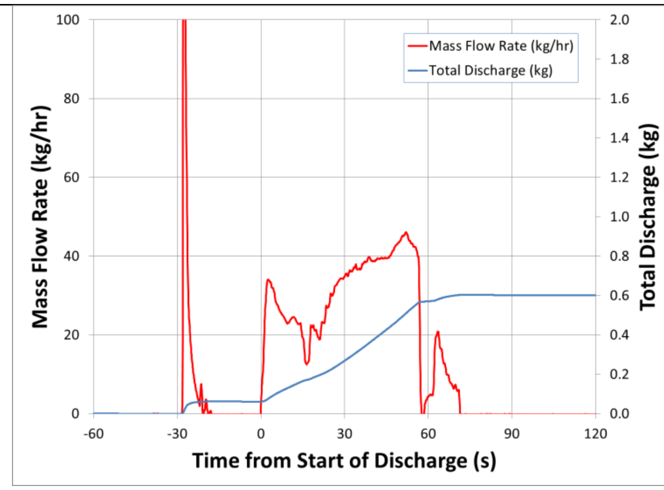
Refrigerant	Release rate (g/s)	Measured Release Quantity (kg)	Ignition Result
R-455A	10	0.60	Ignition

Ignition of the refrigerant occurred 2s after the reach-in cooler door was opened. The flaming was limited to the area in front and the corner area in proximity of the reach-in cooler. The flaming continued for approximately 30s. Note that the refrigerant mass flow controller failed to close on demand at 500 grams and resulted in a total release of 600 grams.

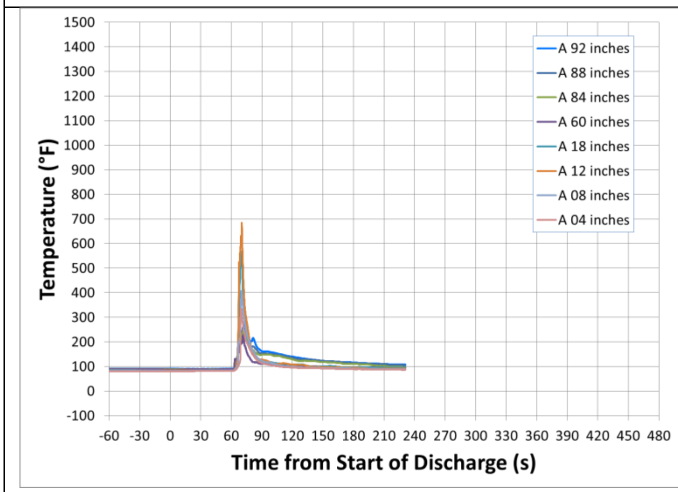
The test results are presented in Figure 108.



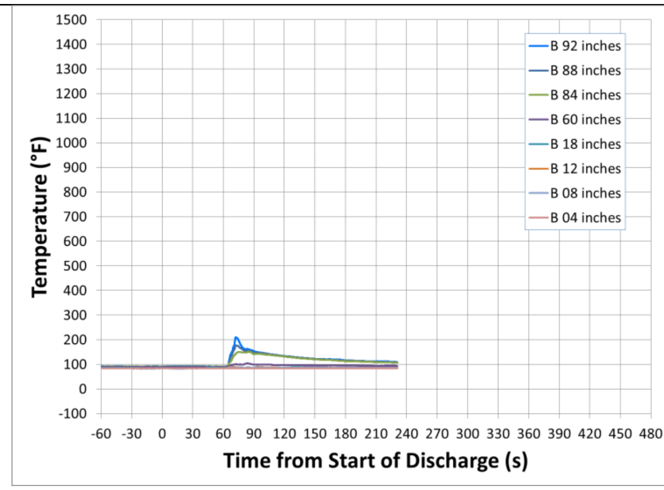
Pressure and Temperature in Pressurizer and Release Tanks



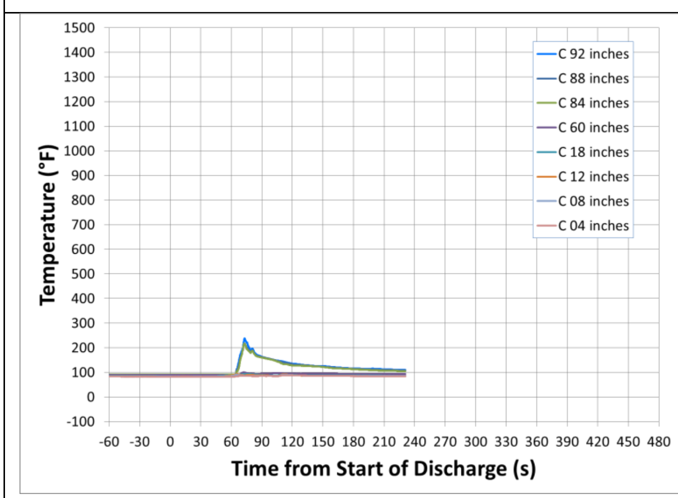
Refrigerant Release Rate



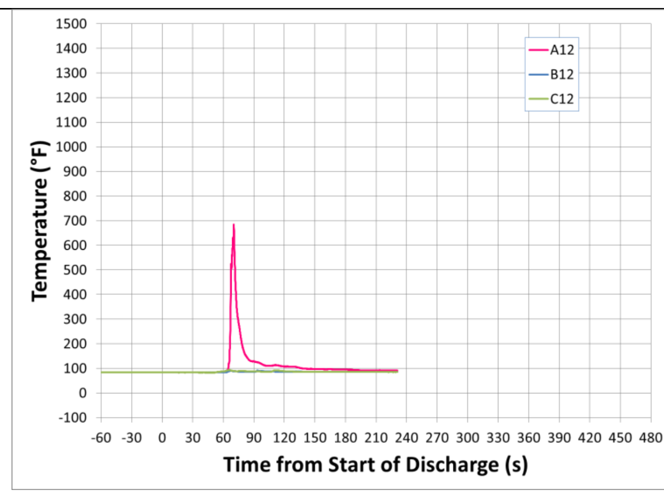
Temperature at Location A



Temperature at Location B



Temperature at Location C



Highest temperature: Temperature 12 in. height above the floor

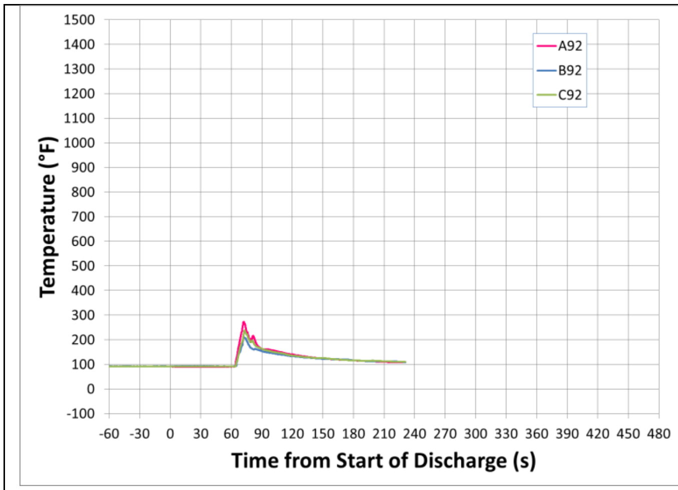
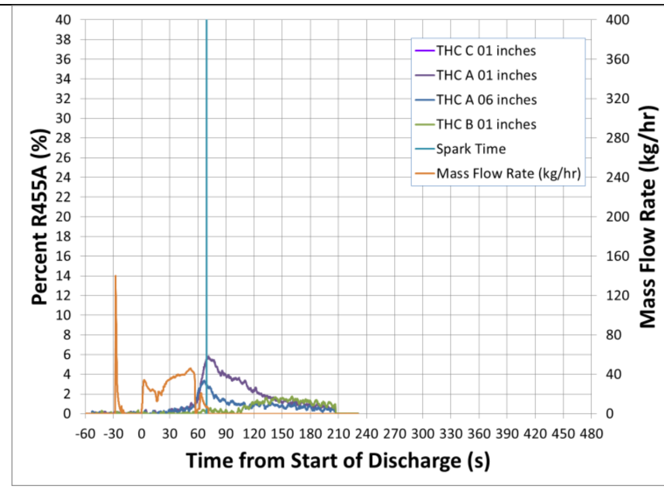
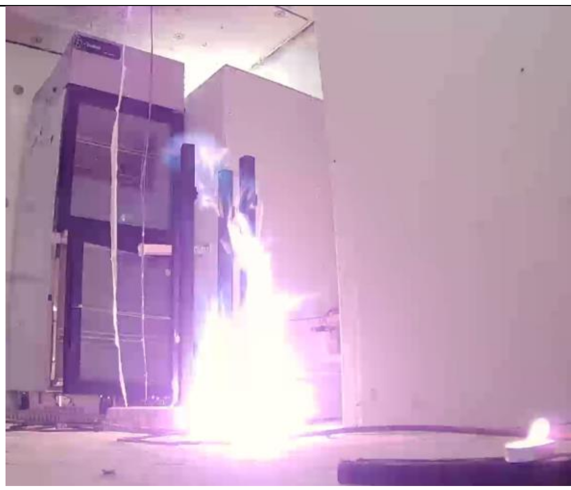
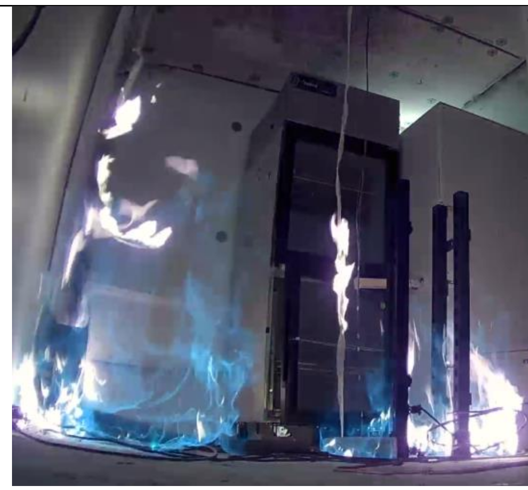
	
Temperature at 92 in. height above the floor	Refrigerant Concentration
	
Flames 2 seconds after the reach-in cooler door was opened.	Flames 6s after reach-in cooler door was opened showing spread of flames to the room corner in proximity of the cooler.

Figure 108 – Test Results for Reach-in Cooler - Cooler01

The flaming was limited to the area in front and the corner area in proximity of the reach-in cooler. The flaming continued for approximately 30s. The highest temperature was recorded at Location A, and 12 inches above the floor.

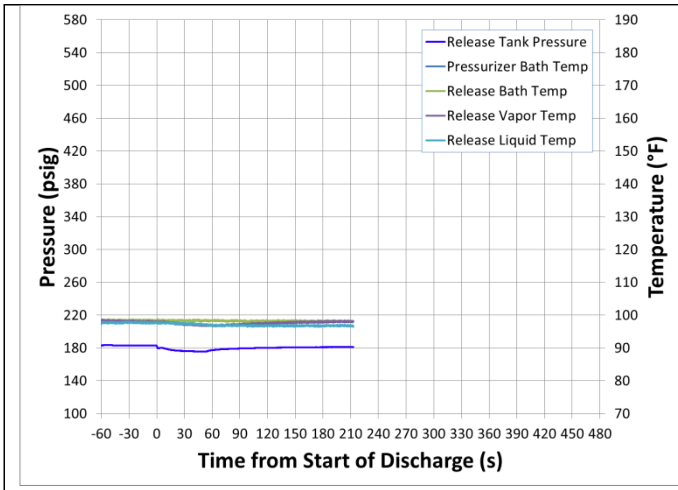
4.5.2.4.2. Cooler02

The test parameters for this test were as follows:

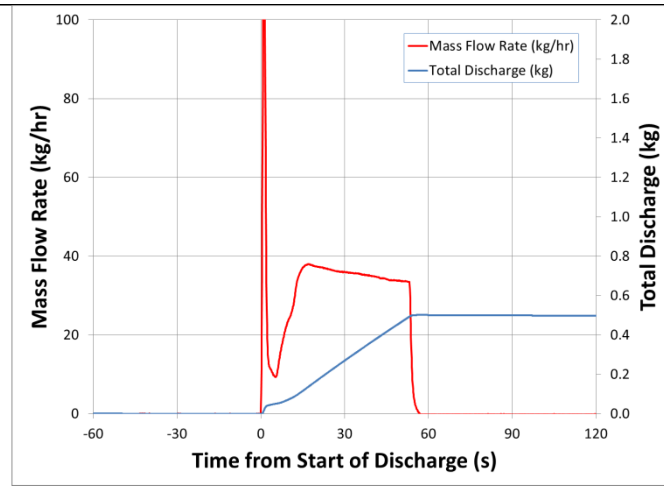
Refrigerant	Release rate (g/s)	Measured Release Quantity (kg)	Ignition Result
R-457A	10	0.50	Ignition

Ignition of the refrigerant occurred 3s after the reach-in cooler door was opened. The flames were limited to the area in front and the corner area in proximity of the reach-in cooler. The flaming continued for approximately 30s.

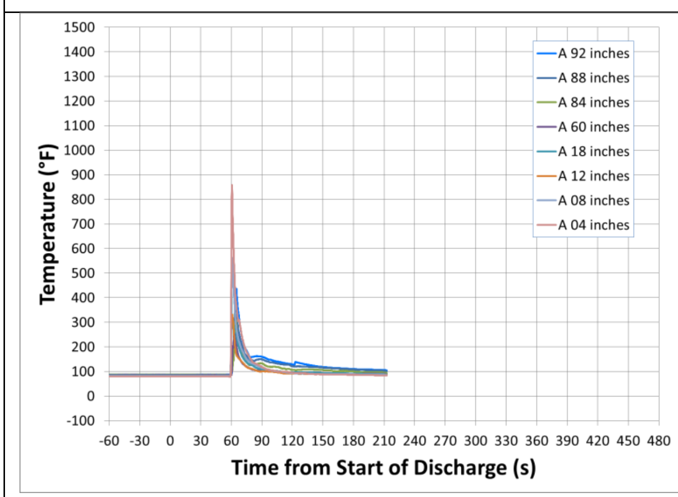
The test results are presented in Figure 109.



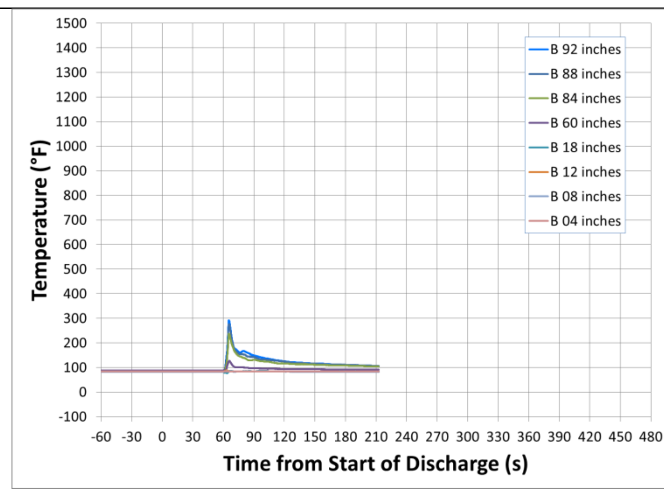
Pressure and Temperature in Pressurizer and Release Tanks



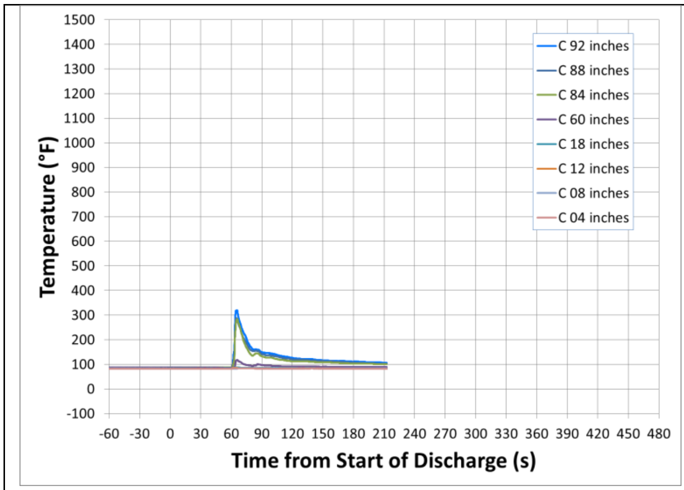
Refrigerant Release Rate



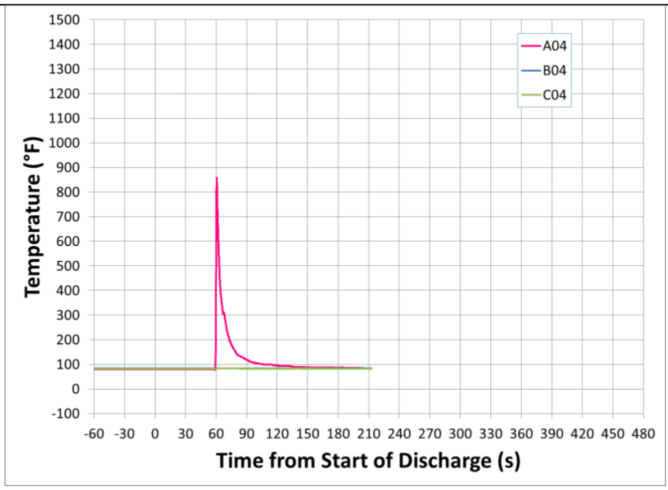
Temperature at Location A



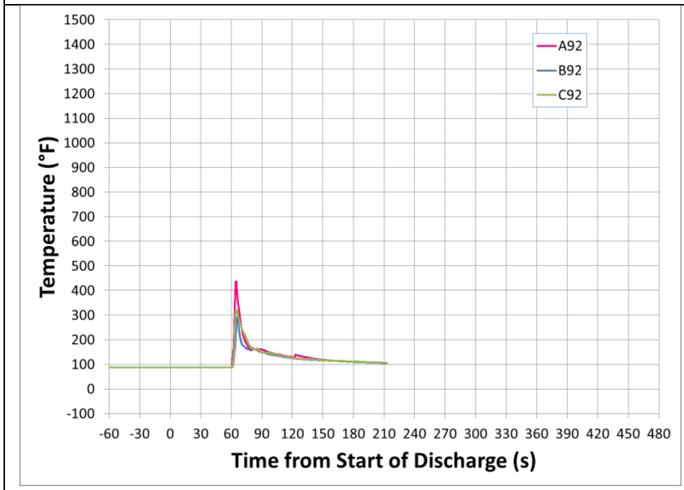
Temperature at Location B



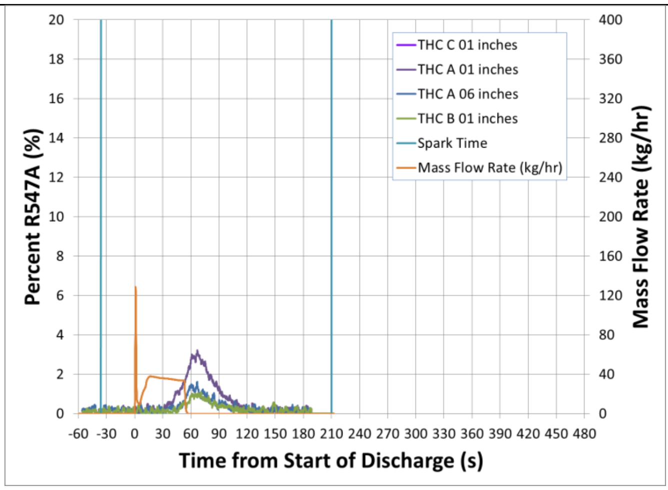
Temperature at Location C



Highest temperature: Temperature 4 in. height above the floor



Temperature at 92 in. height above the floor



Refrigerant Concentration (see notes)

Flames 3 seconds after the reach-in cooler door was opened.

Flames 4s after reach-in cooler door - the fire size grew rapidly.

Flames 6s after reach-in cooler door; the flaming spread into the reach-in cooler.

Figure 109 - Test Results for Reach-in Cooler - Cooler02

The fire size grew rapidly and spread back into the reach-in cooler opening the upper door. The flaming continued for approximately 10s. The highest temperature was recorded at Location A, and 4 inches above the floor.

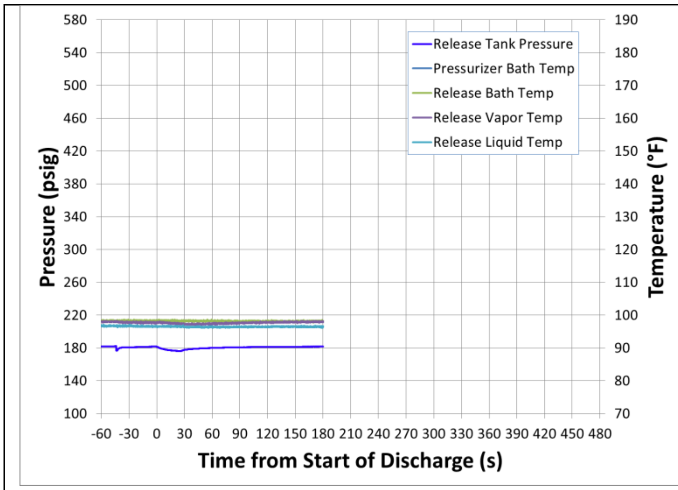
4.5.2.4.3. Cooler03

The test parameters for this test were as follows:

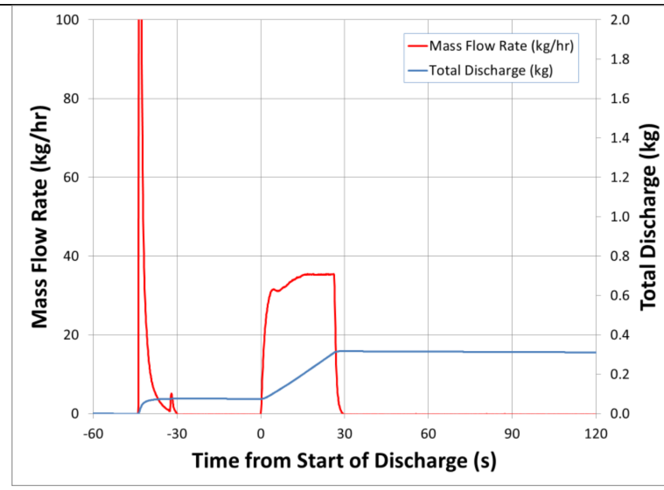
Refrigerant	Release rate (g/s)	Measured Release Quantity (kg)	Ignition Result
R-457A	10	0.30	No ignition [1]

Note: 1 - There was no ignition of the refrigerant but flaring near the pilot flame at Location A was observed.

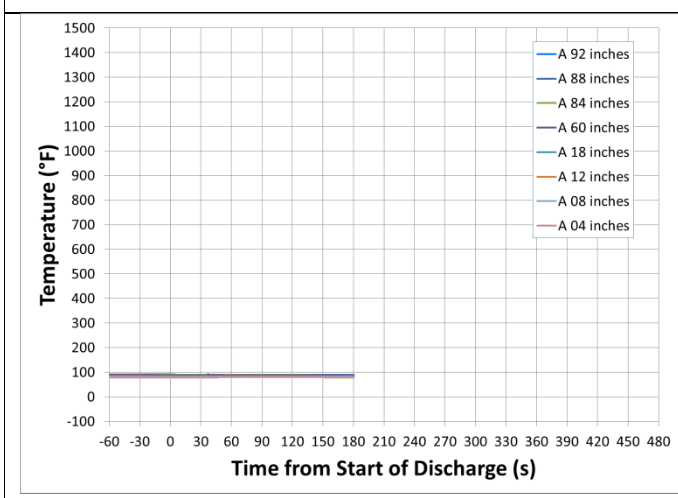
Ignition of the refrigerant gas did not occur. However, small flaring of the refrigerant near the pilot flame was observed at Location A. The flaring continued for approximately 5s. The test results are presented in Figure 110.



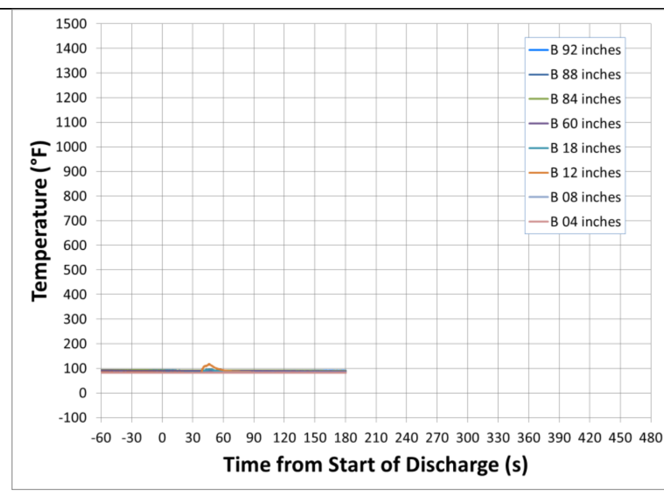
Pressure and Temperature in Pressurizer and Release Tanks



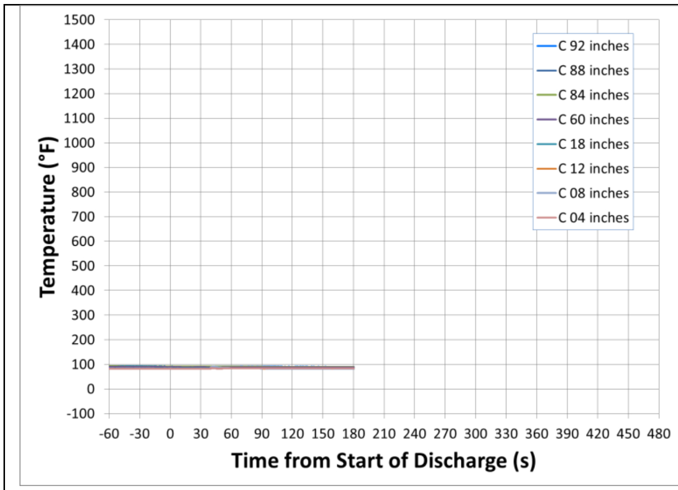
Refrigerant Release Rate



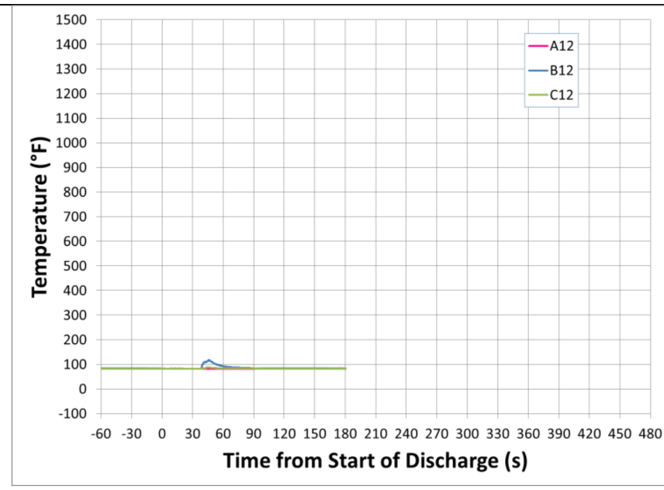
Temperature at Location A



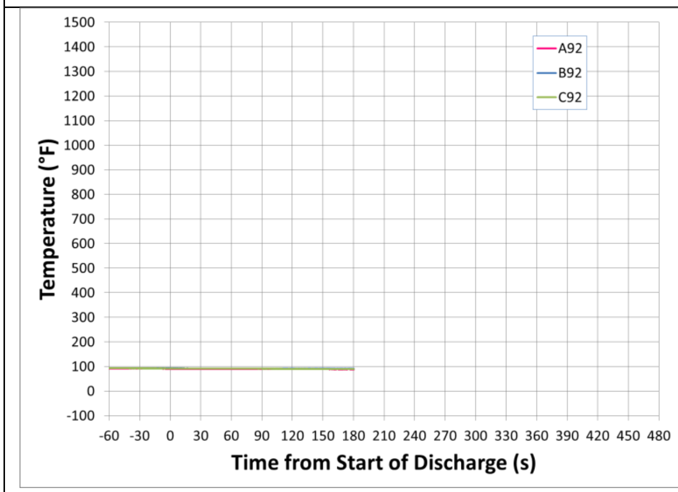
Temperature at Location B



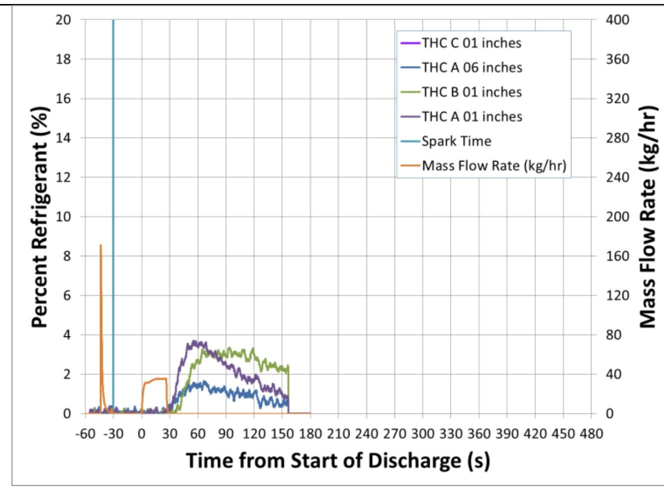
Temperature at Location C



Highest temperature: Temperature 12 in. height above the floor



Temperature at 92 in. height above the floor



Refrigerant Concentration (see notes)

Flaring near pilot flame 5 seconds after the reach-in cooler door was opened.

Figure 110 - Test Results for Reach-in Cooler - Cooler03

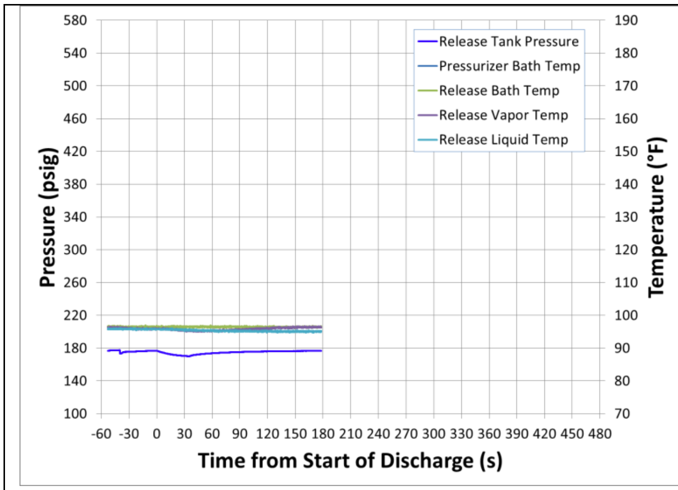
The highest temperature was measured at Location B, 12 inches above the floor.

4.5.2.4.4. *Cooler04*

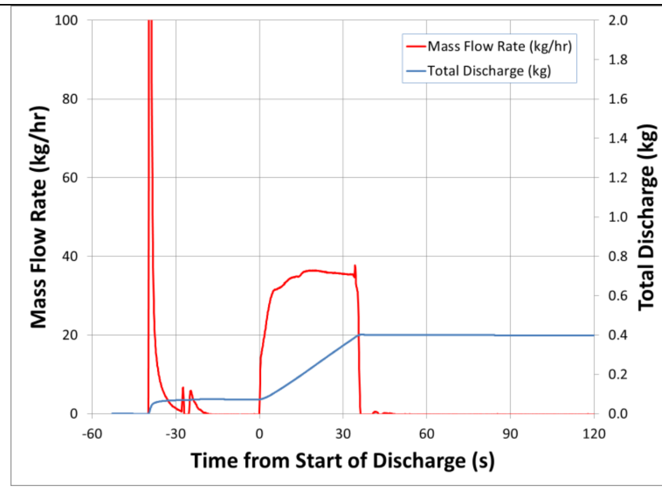
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Measured Release Quantity (kg)	Ignition Result
R-457A	10	0.40	Ignition

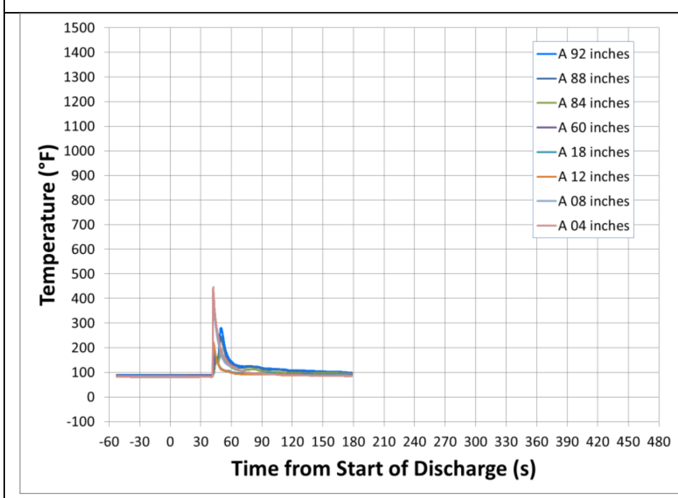
Ignition of the refrigerant gas occurred 3 seconds after the reach-in cooler door was opened. The flames continued for approximately 9 seconds. The test results are presented in Figure 111.



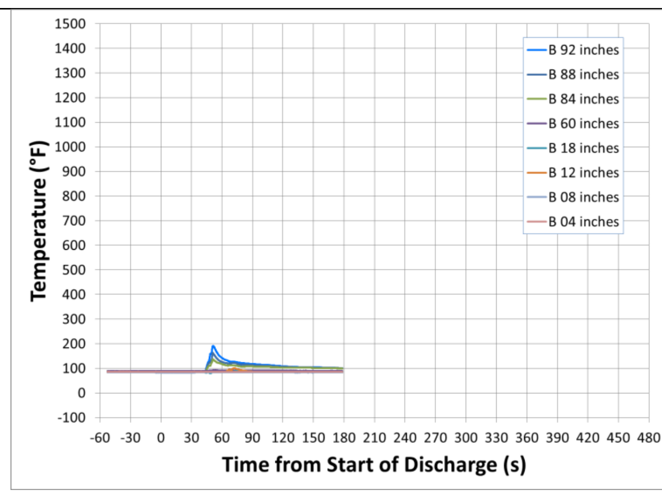
Pressure and Temperature in Pressurizer and Release Tanks



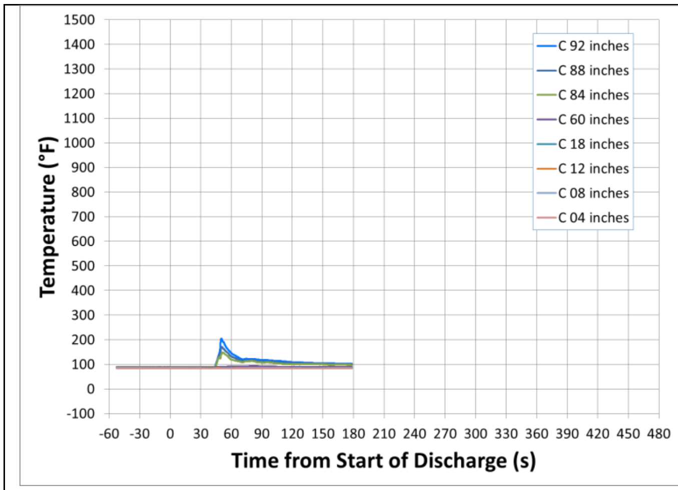
Refrigerant Release Rate



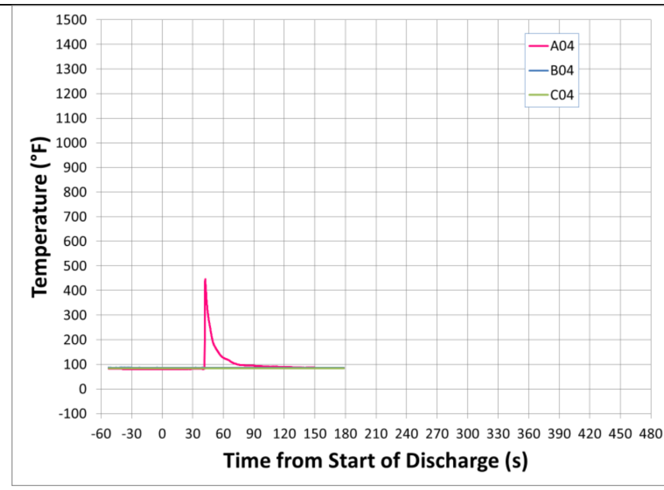
Temperature at Location A



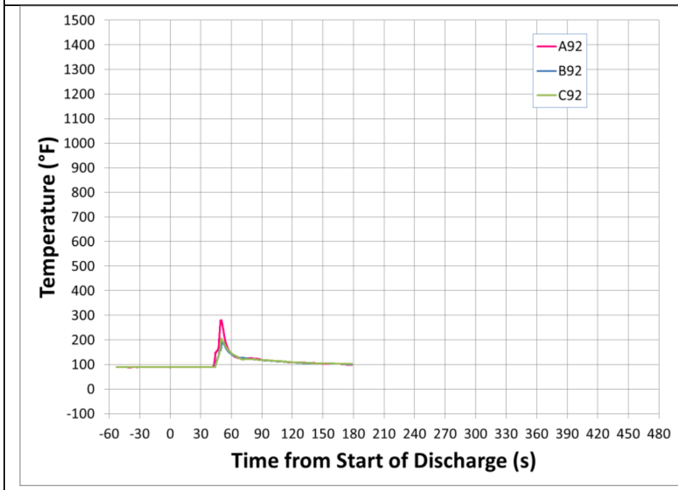
Temperature at Location B



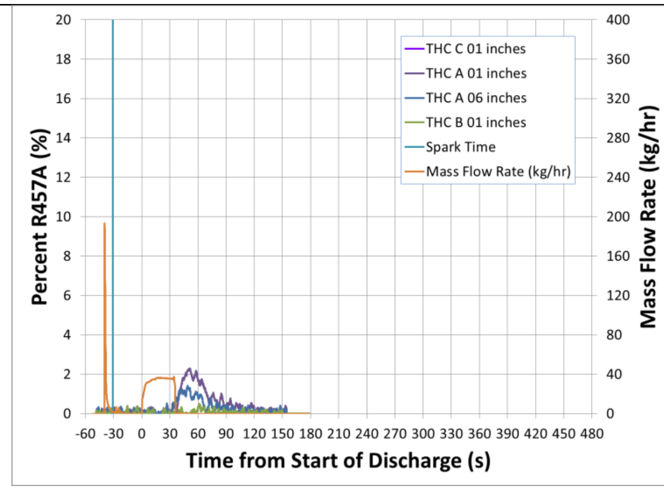
Temperature at Location C



Highest temperature: Temperature 4 in. height above the floor (Location A)



Temperature at 92 in. height above the floor



Refrigerant Concentration (see notes)

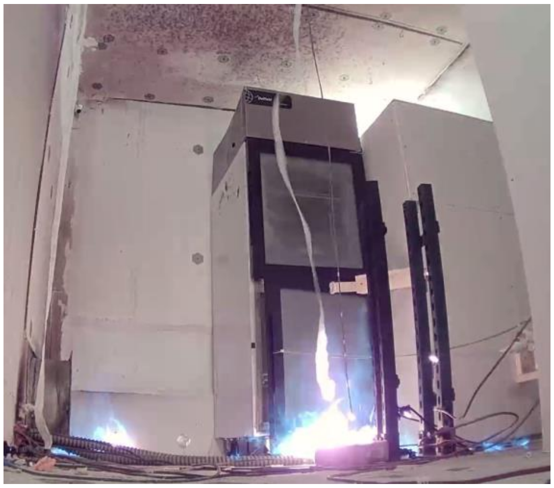
	
Ignition of refrigerant 6 seconds after the reach-in cooler door was opened showing flaming in front and in corner.	Flames 10s after reach-in cooler door is opened enter the cooler

Figure 111 - Test Results for Reach-in Cooler - Cooler04

The fire size grew rapidly and spread back into the reach-in cooler opening the upper door. The flames continued for approximately 12s. The highest temperature was recorded at Location A, and 4 inches above the floor.

4.5.3. Commercial Kitchen Scenario

The commercial kitchen scenario involved the use of a roof top unit with duct work connected to the kitchen space below. Tests were conducted to represent a refrigerant leak in the evaporator. The kitchen dimensions were 14 x 16 x 8 ft. high. Objects representing work surfaces were located in the test area. The test setup is shown in Figure 112, Figure 113, Figure 114, and Figure 115.

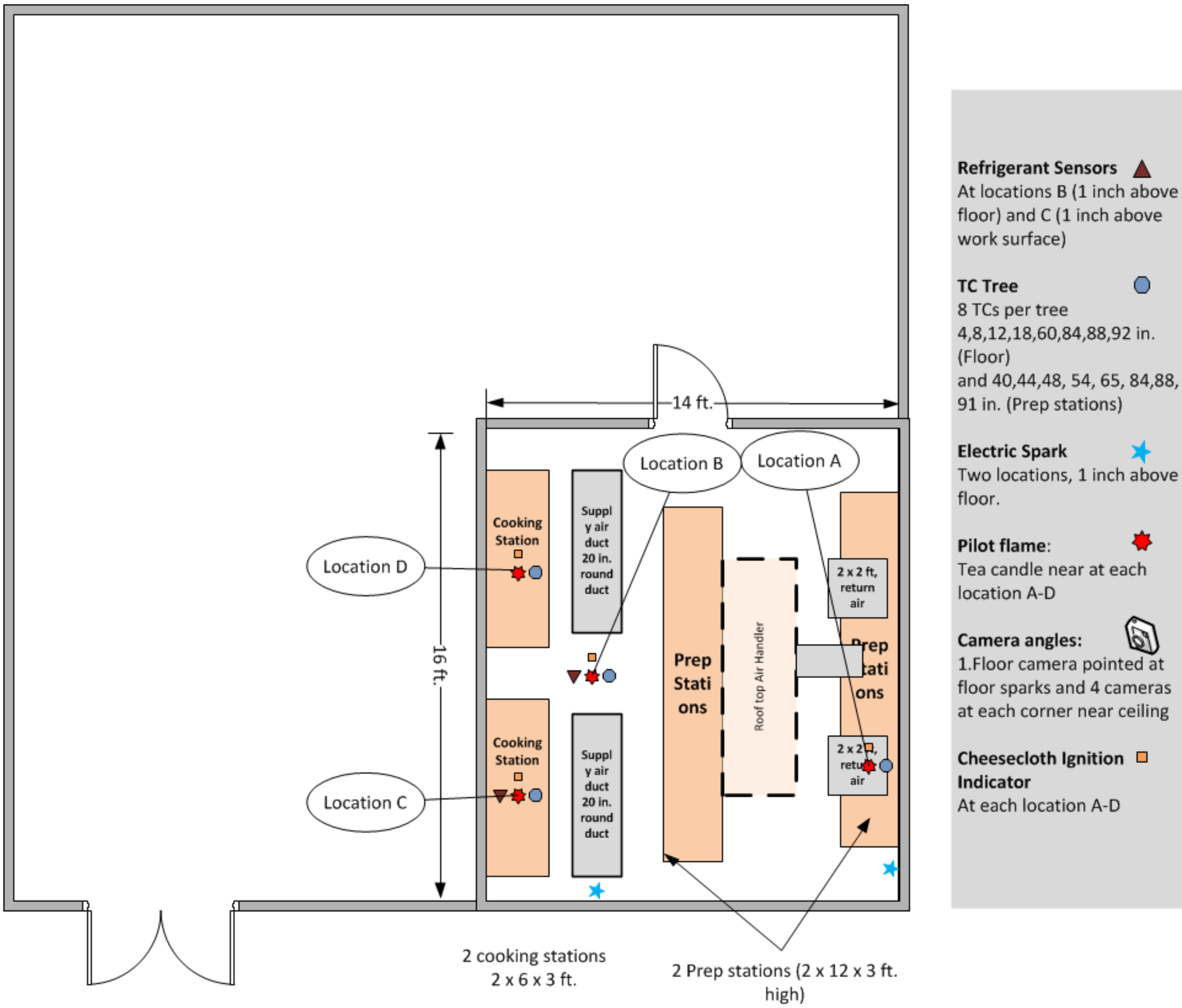


Figure 112 – Commercial Kitchen Layout within the 30'x30' test room

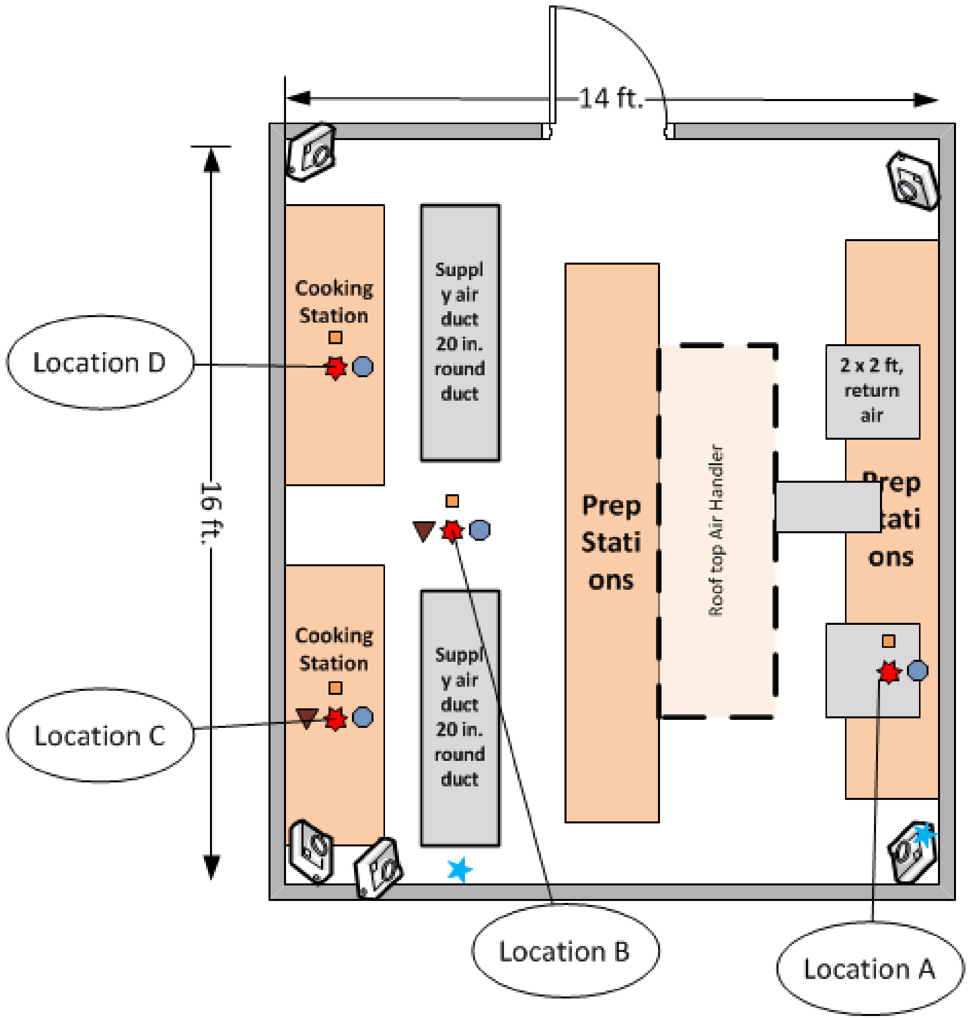


Figure 113 – Larger view of commercial kitchen detail

Figure 114 – Roof top unit (supply side)

Figure 115 - Camera view of kitchen with supply duct work (Locations D, B, and C from foreground to background)

The locations of the instrumentation, and ignition sources were located in clusters at locations A, B, C, and D. The locations relative to the front and right walls are shown in Table 31.

Table 31 – Location of Instrumentation and Ignition Sources

Item	Location	Number	Height above Floor (in.)	Distance from front wall (ft.)	Distance from right wall (ft.)
Refrigerant sensor	B	1	1	8	10
	C	1	1	4	13
Thermocouples	A	8	40, 44, 48, 54, 60, 84, 88, 92	5	1
	B	8	4, 8, 12, 18, 60, 84, 88, 92	8	10
	C	8	40, 44, 48, 54, 60, 84, 88, 92	4	13
	D	8	40, 44, 48, 54, 60, 84, 88, 92	12	13
Pilot flame	A	1	37	5	1
	B	1	1	8	10
	C	1	37	4	13
	D	1	37	12	13
Electric Arc	Right	1	1	4 inches	3
	Left	1	1	4 inches	9.5

4.5.3.1. Refrigerant Release

The commercial kitchen scenario involved the use of a roof top unit with duct work connected to the kitchen space below. The release quantities for R-32 and R-452B were based on a Working Group 9 draft version of IEC 60335-2-40 (Annex GG section: GG.10.1) [13]. The LFL (kg/m³) was adjusted for the elevation of 200 meter (650 feet). The values provided by the AHRTI PMS for these two refrigerants were 6.89 kg for R-32 and 7.07 kg for R-452B, based on a room area of 224 ft² (20.8m²) and a default release height of 2.20 meters (7.22 ft.). The refrigerant release rate was 100 g/s through a ½ inch diameter tube. The discharge tube was placed at one of the return bends on the roof top unit evaporator as shown in Figure 116. The length of the tube was approximately 5 meters and was attached to a 1 by ½ inch reducer at the exit of the mass flow control valve.

[13] International Electrotechnical Commission (IEC), 60335-2-40, Household and similar electrical appliances – Safety – Part 2-40: Particular requirements for electrical heat pumps, air-conditioners and dehumidifiers, Developed by IEC Subcommittee 61D, Appliances for air-conditioning for household or similar use, Working Group 9.

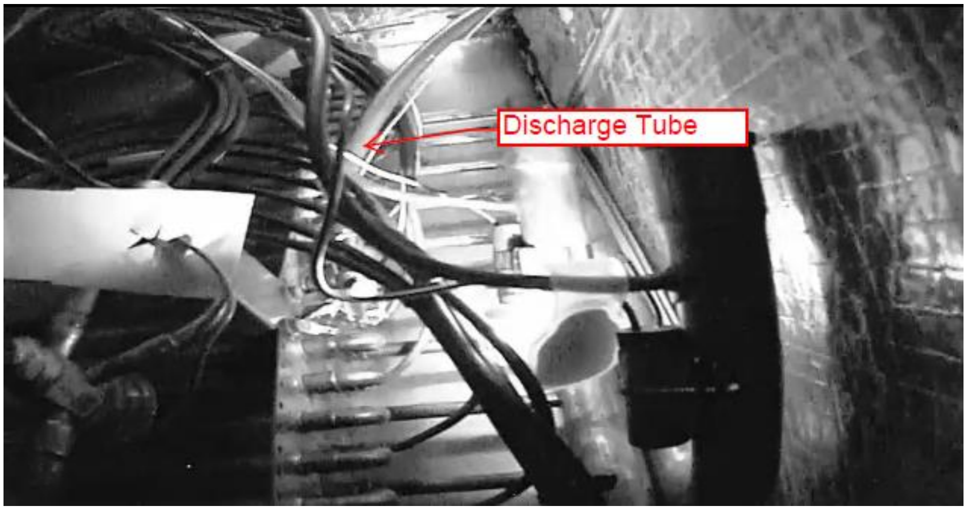


Figure 116 – Video camera view showing discharge tube near return bends

Each test involved the use of the roof top unit blower motor to simulate a mitigating action at either 30 seconds or 60 seconds after the start of the release. Due to the size of the kitchen volume, the motor speed was set to a differential pressure across the fan of 0.269 ± 0.22 mmHg (0.144 ± 0.12 in. H_2O). A test matrix for the kitchen scenario is shown in Table 32. The refrigerant delivery system was limited to approximately 7 kg. For this reason, the volume of the kitchen was reduced compared to the original plan in order to keep the mixed LFL % at the originally intended value.

Table 32 – Test Matrix for Kitchen scenario

Refrigerant	Test Number	Planned Discharge (kg)	Release Rate (g/s)	Mitigation Action time after start of release
R-452B	Kitchen01	7.07	100	30 seconds
R-32	Kitchen02	6.89	100	30 seconds
R-452B	Kitchen03	7.07	100	60 seconds
R-32	Kitchen04 [1]	6.89	100	60 seconds
R-32	Kitchen05	6.89	100	60 seconds

Note: [1] Kitchen04 test was invalid due to the lack of the pressurizer during the discharge. The test was repeated in Kitchen05 with the pressurizer correctly aligned.

4.5.3.2. Test Procedure

The following procedure was used to initiate each test:

1. Confirm pressure and release refrigerant tank pressure and temperatures.
2. Confirm the ISO test room temperature and humidity were as high as the heating system could achieve. Significant heat was lost due to the roof top unit exposure to the cold air in the laboratory space.
3. Light the candles and turn off the lab HVAC and humidity systems.

4. Initiate data acquisition and video capture 1 minute prior to discharging refrigerant.
5. Develop vacuum (less than 1mm Hg) in piping connecting the pressure and release tanks as well between the release tank and flow meter.
6. Open the valve between the pressure and release tanks, and hold for 5 seconds.
7. Open the valve between release tank and the flow meter and hold for 5 seconds.
8. Energize the solenoid valves to enable refrigerant discharge.
9. Open the control valve to initiate refrigerant discharge through the mass flow meter.
10. When refrigerant flow begins, turn on the electric arcs and start a stop watch for turning on the blower motor.
11. At 30 or 60 seconds after the start of discharge, energize the blower motor at 26 Hz.
12. At the completion of the discharge, de-energize the solenoid valves.
13. Continue to collect data until all flaming has ceased for at least 2 minutes.
14. Vent the test room.

After each test, the test facility was exhausted through UL's smoke abatement system, and the conditions in the facility were monitored with open path gas FT-IR. Staff re-entered the test facility for the next only after the gas FT-IR indicated normal ambient conditions.

4.5.3.3. Summary of Findings – Commercial Kitchen Tests

No ignition was observed in any of the five kitchen tests. In every experiment, some of the candles on the work surfaces were extinguished due to either increased cold air movement or the action of the blower motor. There is a possibility that the candles were extinguished due to lack of oxygen from initial high concentration of refrigerant (far above the UFL). A recommendation for future testing of this scenario is to use natural gas burners such as may be found in a commercial kitchen. A safety measure for such testing necessarily involves the use of a positive means of shutting off the natural gas supply in the case that either extinguishment or ignition occurs.

It was observed that very little mist was seen entering the kitchen during the first two tests (30 seconds mitigation time). At 30 seconds, less than ½ of the total discharge had been released.

In the last three tests (60 second mitigation time), it was observed that mist began to enter the kitchen through the supply ductwork after 30 seconds. After the blower motor was energized, a large cloud of mist was seen entering the kitchen through the supply ductwork. From other Task 2 tests, it was observed that the mist is coincident with the highest refrigerant concentrations.

This data seems to indicate that most of the refrigerant remained within the RTU or the roof top ductwork up until the blower motor was energized.

The refrigerant concentration sensors showed concentrations below the LFL in all experiments. Figure 117 shows the concentration at Location B (floor level) and Figure 118 shows the concentration at location C (work surface). This data shows that the cold mix of refrigerant and air drops quickly to floor level. The concentrations at the work surface (Location C) begin to increase and equalize with Location B only after the fan motor has been operating for about one minute.

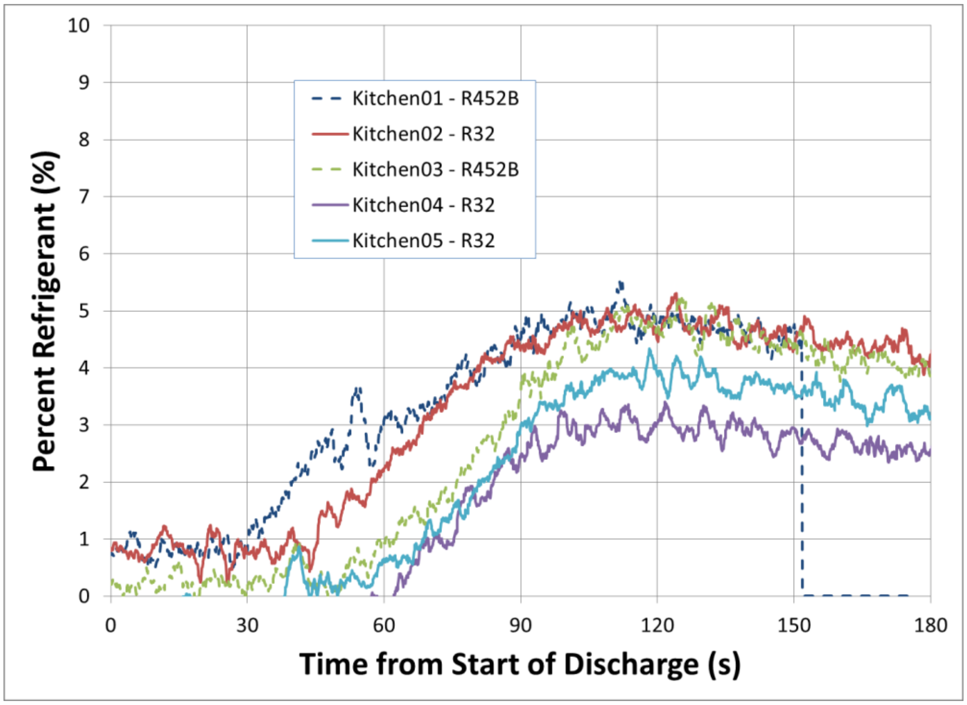


Figure 117 – Refrigerant Concentration Location B (1 inch above the floor)

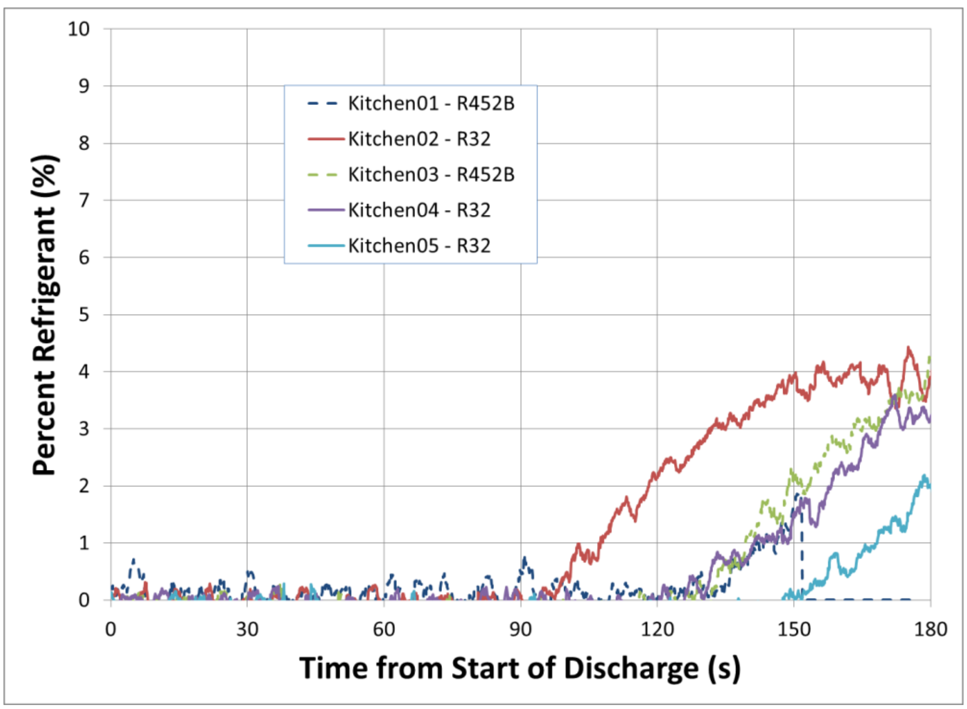


Figure 118 - Refrigerant Concentration Location C (1 inch above the work surface)

The Kitchen04 test demonstrated the need for the pressurizer to be properly aligned in the discharge path. Use of the release tank alone results in a fast pressure drop (due to evaporative cooling) that prevents the discharge of the planned amount.

4.5.3.4. Results

A summary of test results are presented in Table 33 and Table 34.

Table 33 – Commercial Kitchen Scenario Summary

Refrigerant	Test Number	Mitigation Action time after start of release (s)	Max Pressure (mmHg)	Max. Temperature and Location (°F /Location)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	Result
R-452B	Kitchen01	30	0.03	151 / B08*	88	85	No Ignition
R-32	Kitchen02	30	0.02	173 / B12*	83	81	No Ignition
R-452B	Kitchen03	60	0.01	159 / B18*	86	84	No Ignition
R-32	Kitchen04	60	0.01	162 / B12*	83	81	No Ignition
R-32	Kitchen05	60	0.01	98 / D48	87	86	No Ignition

* These high temperatures are suspect because the videos show no signs of combustion. Electromagnetic interference is suspected at Location B's thermocouple tree.

Table 34 – Commercial Kitchen Discharge Mass, Rate, and Maximum Concentration

Refrigerant	Test Number	Measured Discharge (kg)	Planned Discharge (kg)	Measured Rate (g/s)	Maximum Refrigerant Concentration Measured (%)	Average Pressure Diff. (Return and Supply) (mmHg)	Std. Dev. (mmHg)
R-452B	Kitchen01	7.10	7.07	93.03	5.5	0.270	0.019
R-32	Kitchen02	6.92	6.89	83.00	5.3	0.271	0.018
R-452B	Kitchen03	7.09	7.07	81.94	5.3	0.274	0.019
R-32	Kitchen04	6.74	6.89	20.41*	4.9	0.273	0.017
R-32	Kitchen05	6.90	6.89	89.80	4.6	0.266	0.017

* -- The low measured rate of discharge is due to the lack of the pressurizer in this test.

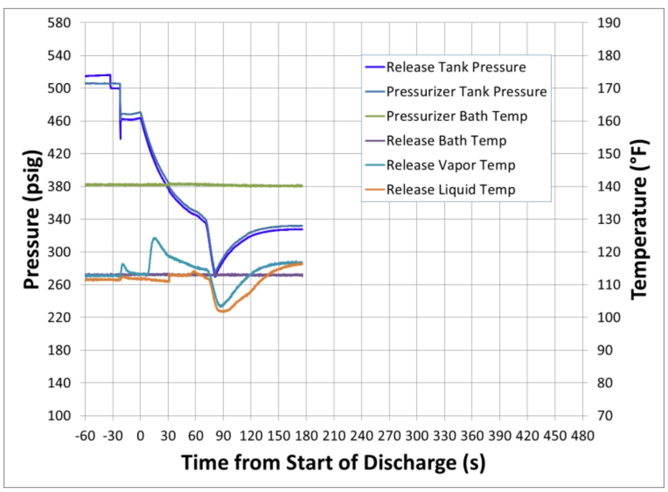
The test results for the tests are presented herein.

4.5.3.4.1. Kitchen01:

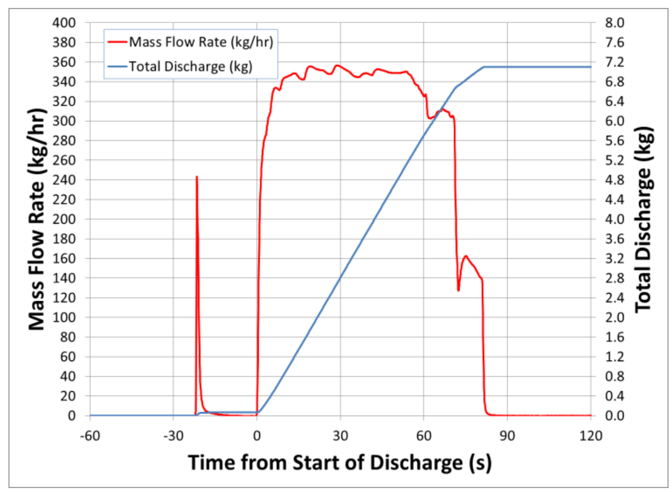
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Mitigation (Blower Energized) time	Ignition Result
R-452B	100	7.07	Start of Discharge + 30 seconds	No ignition

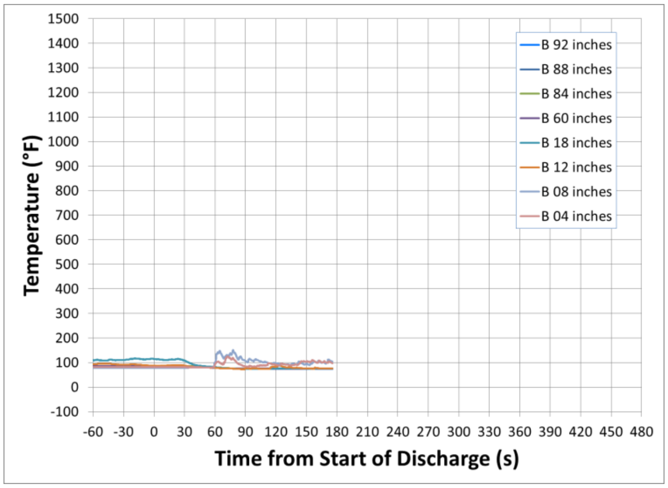
There was no ignition during the test. The candles were extinguished shortly after the blower motor was started. The reason for the extinguishment would require further investigation. Shortly before the blower motor started there was increased flame size at the candles at locations A, C, and D. The candle at floor level (location B) remained lit throughout the test. Selected data from this test are shown in Figure 119.



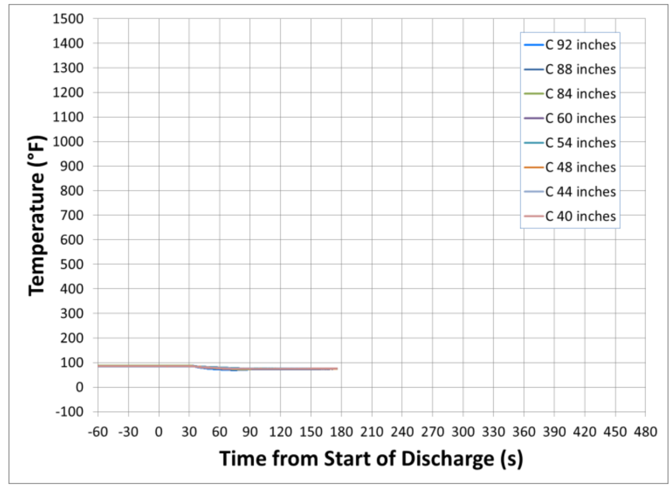
Pressure and Temperature in Pressurizer and Release Tanks



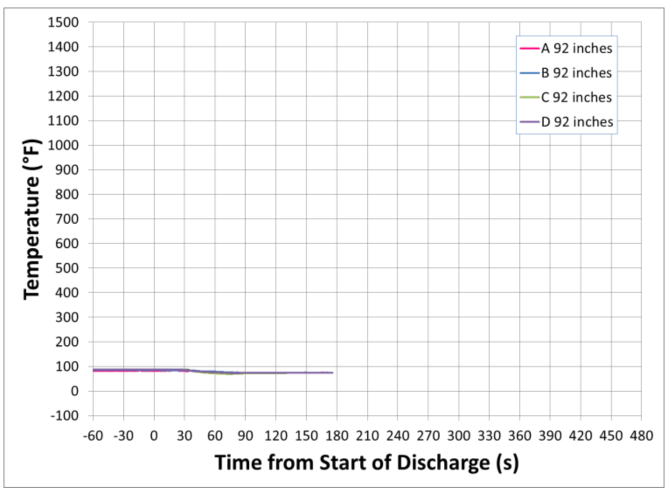
Refrigerant Release Rate



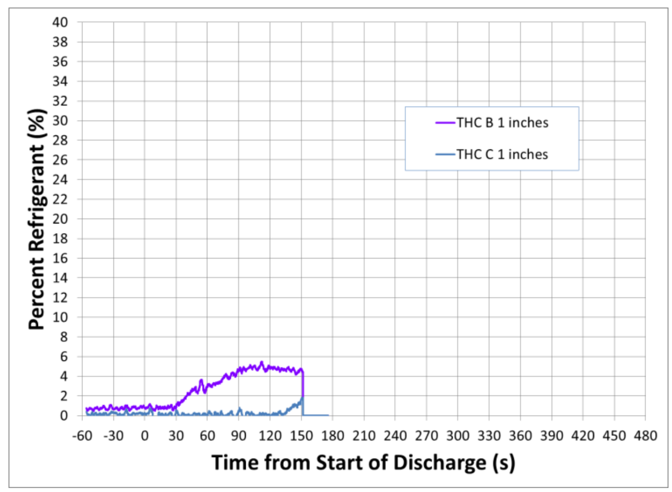
Temperature at Location B



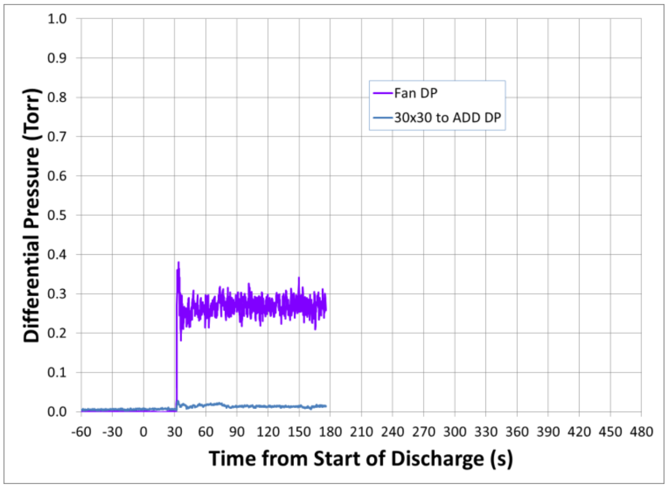
Temperature at Location C



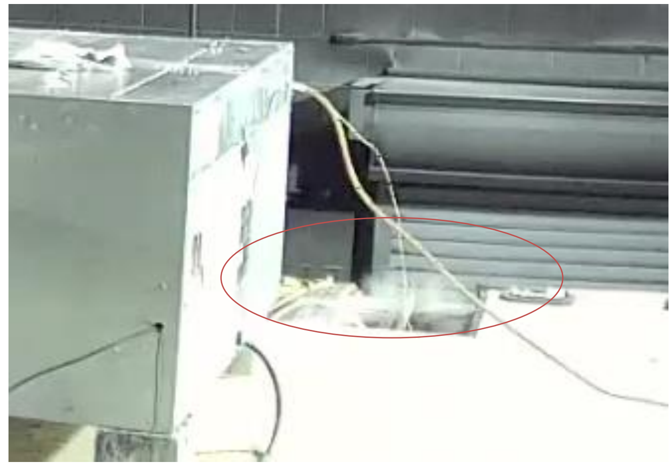
Temperature at 92 in. height above the floor



Refrigerant Concentration

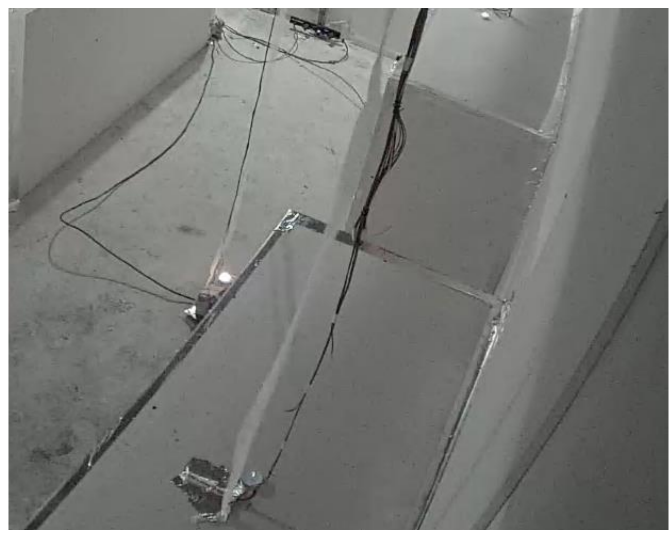


Room and Blower Differential Pressure



Condensate Drain on RTU showing a mist escaping through this route. The power cable for the fan motor was routed through the condensate drain.

Candles Flaring up at 31 seconds after the beginning of the discharge due to increased refrigerant concentration.



Candles at Locations A, C, D extinguished at 35 seconds after blower motor up to speed (26 Hz).

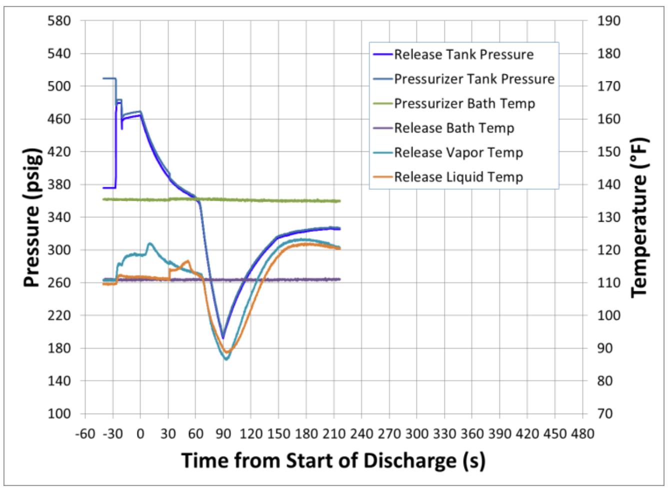
Figure 119 – Data from Kitchen01

4.5.3.4.2. Kitchen02:

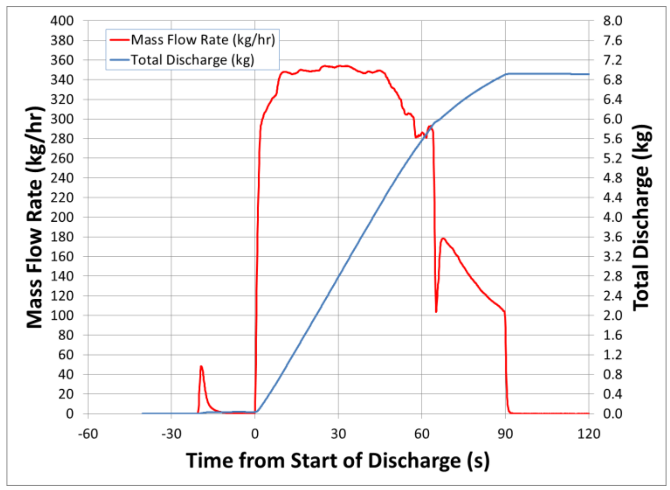
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Mitigation (Blower Energized) time	Ignition Result
R-32	100	6.89	Start of Discharge + 30 seconds	No ignition

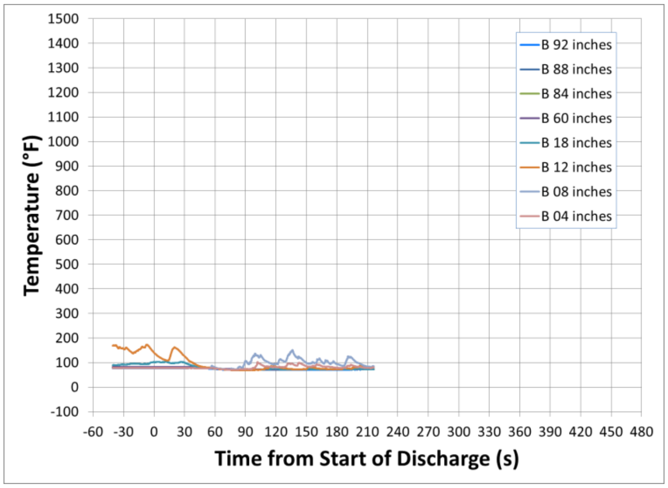
There was no ignition during the test. The candles at locations A and C were extinguished shortly after the blower motor was started. The reason for the extinguishment would require more experimentation. From the video it appears that the candles were extinguished due to air movement caused by the blower motor. The candle at locations B and D remained lit throughout the test. Selected data from this test are shown in Figure 120.



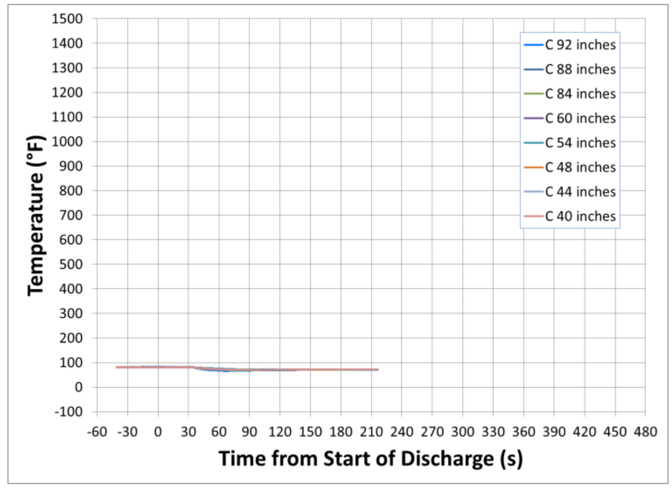
Pressure and Temperature in Pressurizer and Release Tanks



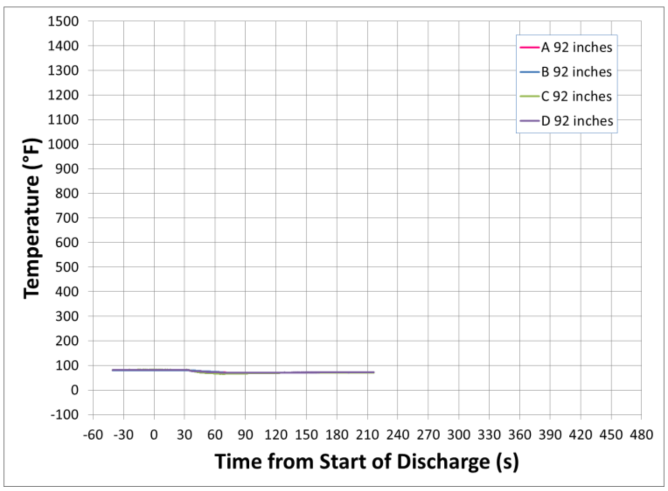
Refrigerant Release Rate



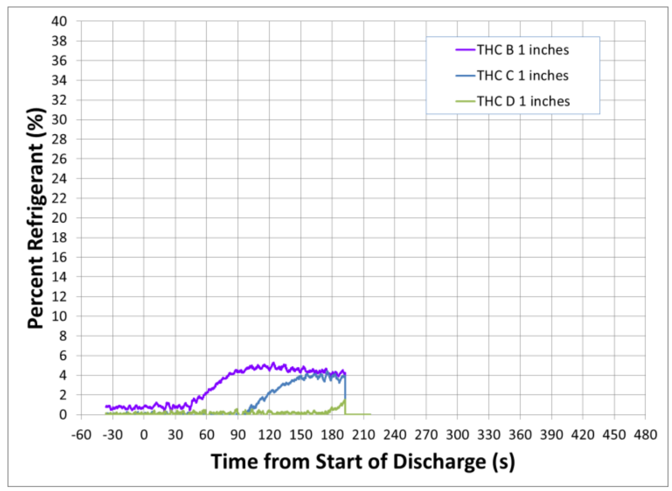
Temperature at Location B



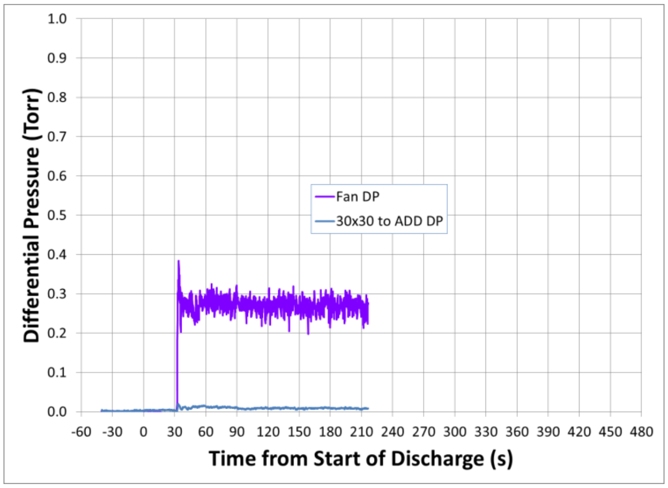
Temperature at Location C



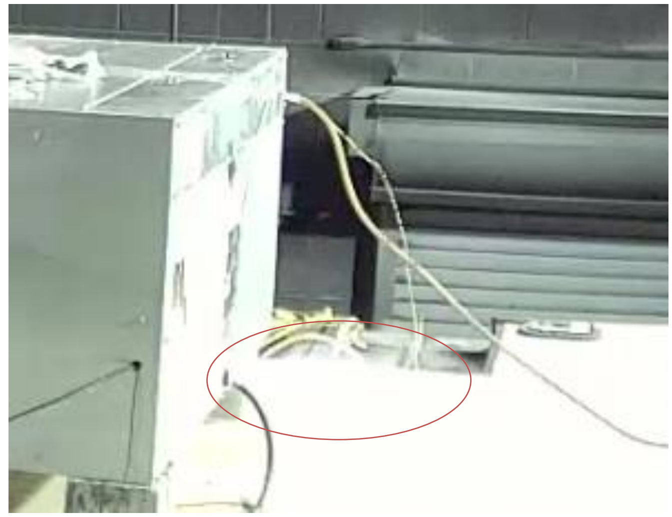
Temperature at 92 in. height above the floor



Refrigerant Concentration



Room and Blower Differential Pressure



Condensate Drain on RTU showing a mist escaping through this route. The power cable for the fan motor was routed through the condensate drain.

Candles flickering at 34 seconds after the beginning of the discharge. The blower motor had been started 2 seconds prior.

Candle at Locations C extinguished at 42 seconds after after the beginning of the discharge. The blower motor had been operating for 10 seconds. The candle at location A extinguished 11 seconds later.

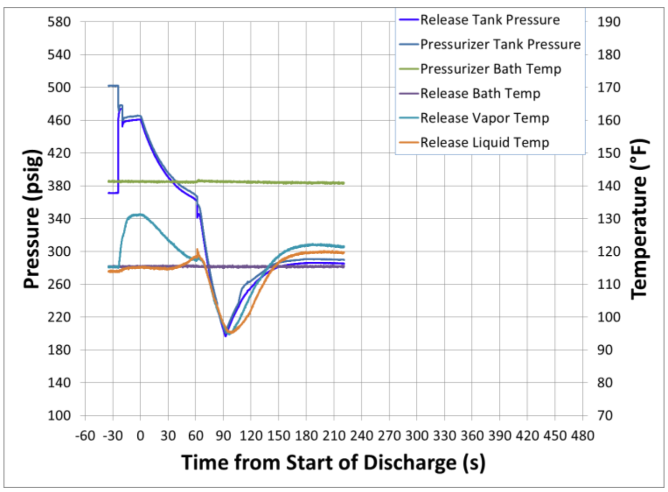
Figure 120 – Data from Kitchen02

4.5.3.4.3. Kitchen03:

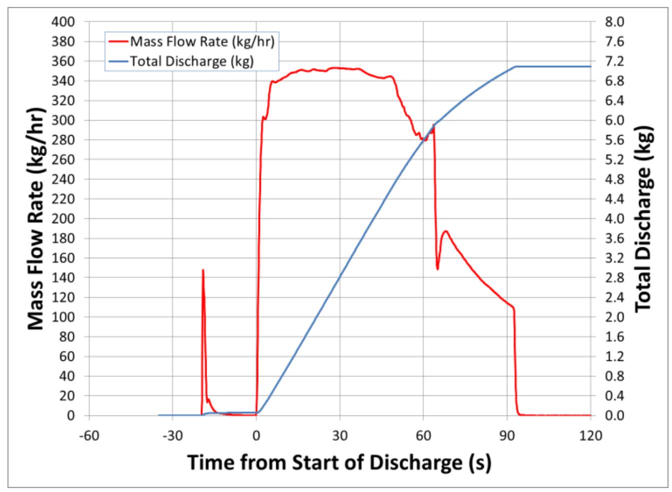
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Mitigation (Blower Energized) time	Ignition Result
R-452B	100	7.07	Start of Discharge + 60 seconds	No ignition

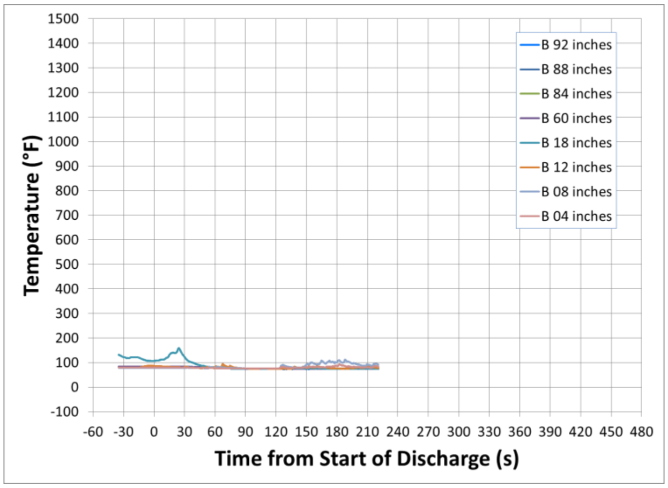
There was no ignition during the test. The candles at locations C and D were extinguished shortly after the blower motor was started. From the video it appears that the candles were extinguished due to air movement caused by the blower motor. The candles at locations A and B remained lit throughout the test. Some flaring of the candles was observed in the 20 seconds after the beginning of the discharge. Selected data from this test are shown in Figure 121.



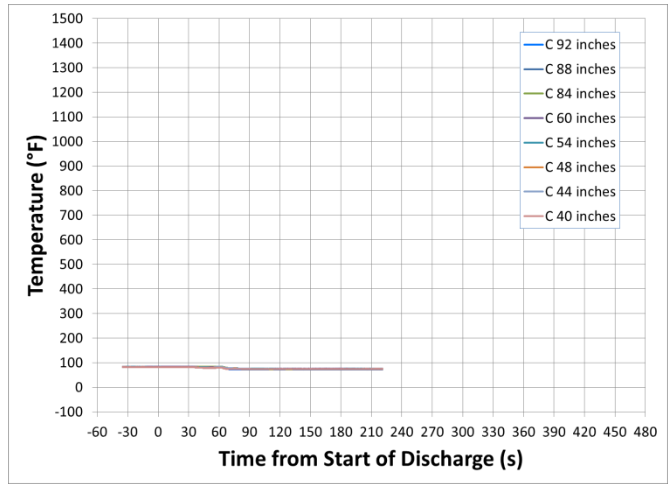
Pressure and Temperature in Pressurizer and Release Tanks



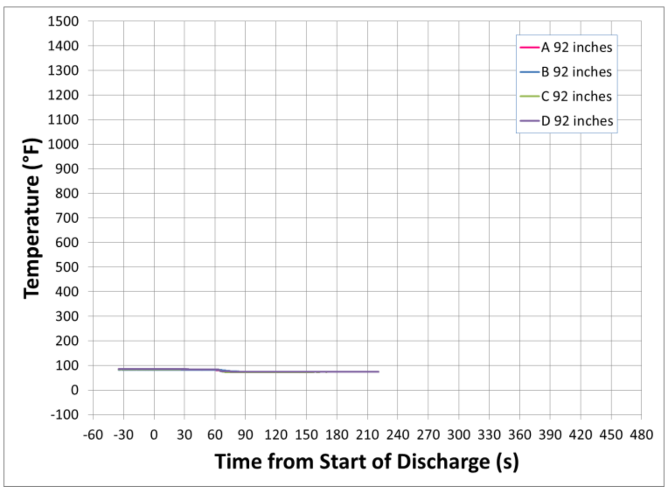
Refrigerant Release Rate



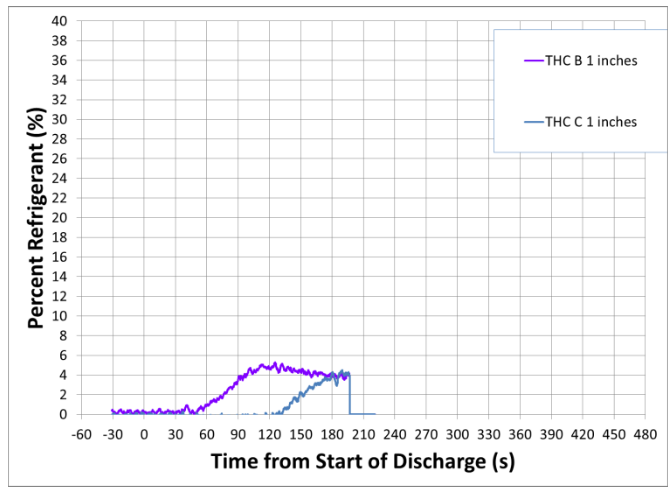
Temperature at Location B



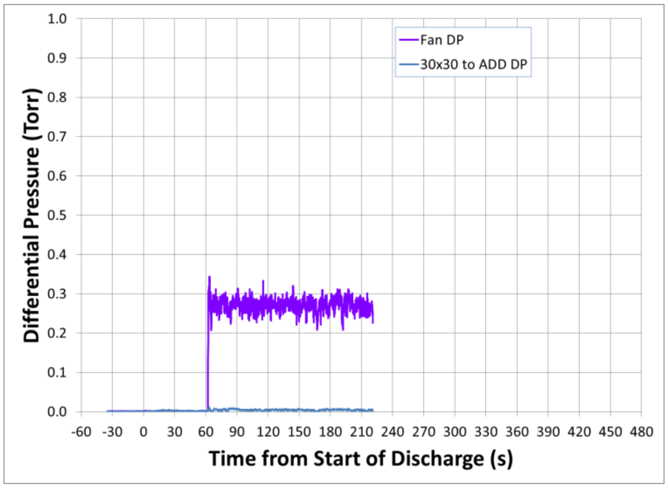
Temperature at Location C



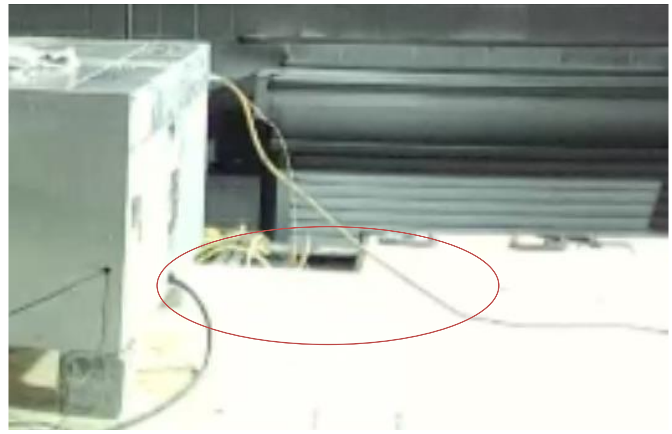
Temperature at 92 in. height above the floor



Refrigerant Concentration



Room and Blower Differential Pressure



Condensate Drain on RTU showing a barely visible mist escaping through this route. The power cable for the fan motor was routed through the condensate drain. The mist is more visible on the video of this test.

Candles flaring up at 23 seconds after the beginning of the discharge.

Mist exiting the supply duct at 62 seconds after the beginning of the discharge. The blower motor had been started 2 seconds prior to this frame. Candles at locations C and D extinguished 17 seconds later. The candles at locations A and B remained lighted throughout the test.

Figure 121 – Data from Kitchen03

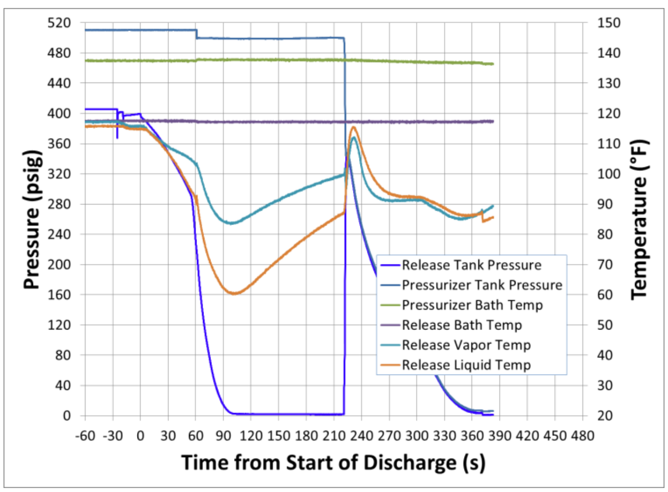
4.5.3.4.4. Kitchen04:

The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Mitigation (Blower Energized) time	Ignition Result
R-32	100	6.89	Start of Discharge + 60 seconds	No ignition

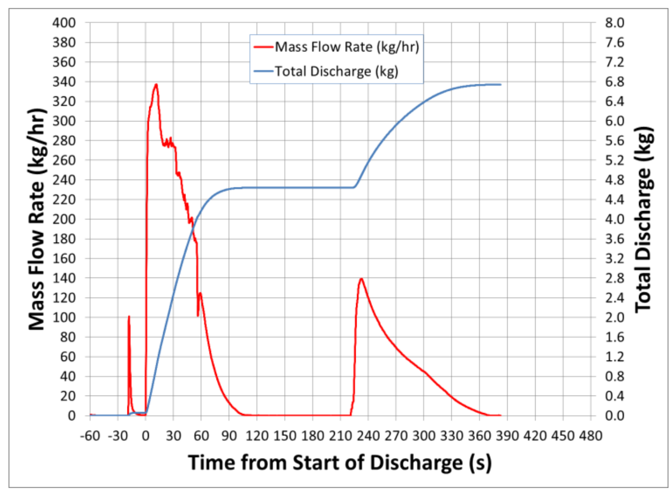
This test was invalid due to improper alignment of the pressurizer tank prior to beginning the discharge. It is included in the report to show the effect of the pressurizer's absence.

There was no ignition during the test. The candles at locations A, C, and D were extinguished at various times before and after the blower motor started. The reason for the extinguishment would require more experimentation. The candle at location B remained lit throughout the test. Selected data from this test are shown in Figure 122.



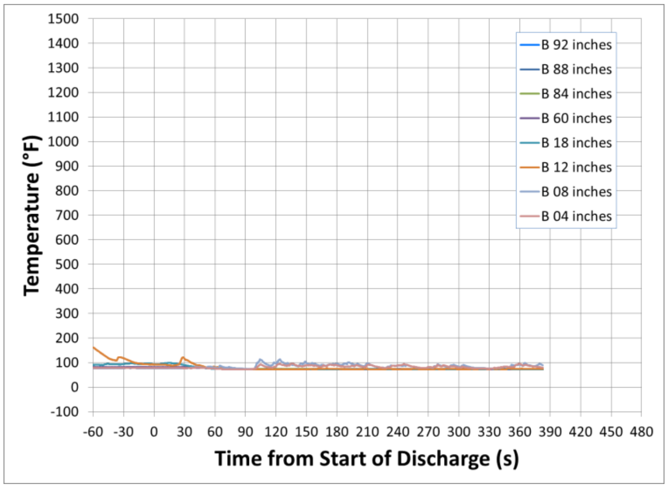
Pressure and Temperature in Pressurizer and Release Tanks

The pressurizer was not properly aligned at the beginning of this test. It was aligned properly 220 seconds after the beginning of the discharge.

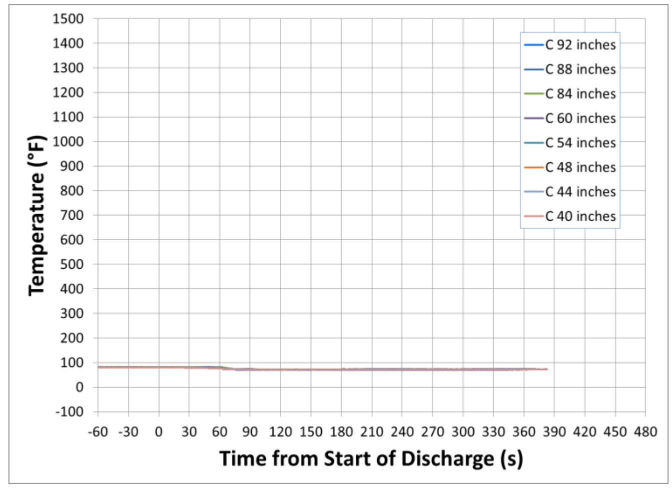


Refrigerant Release Rate

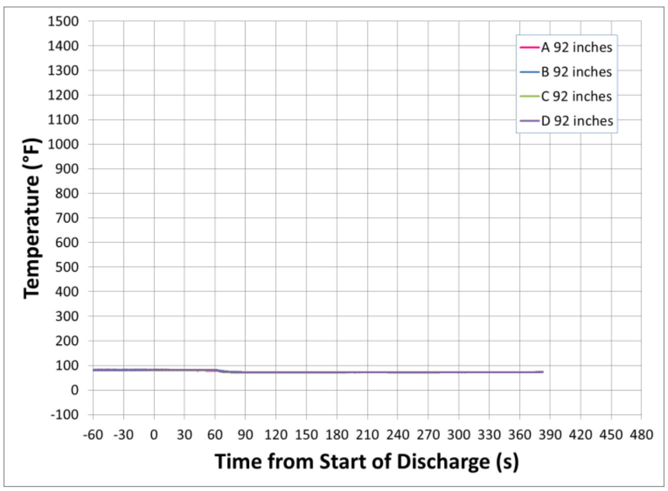
Due to the lack of the pressurizer the total planned discharge was not achieved. This test is repeated in the Kitchen05 test.



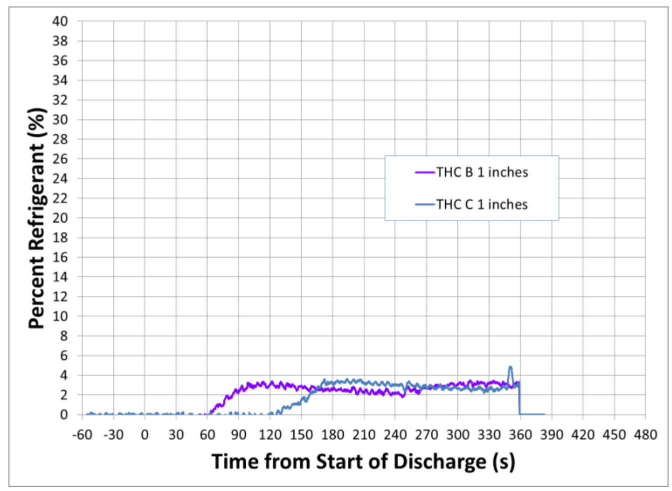
Temperature at Location B



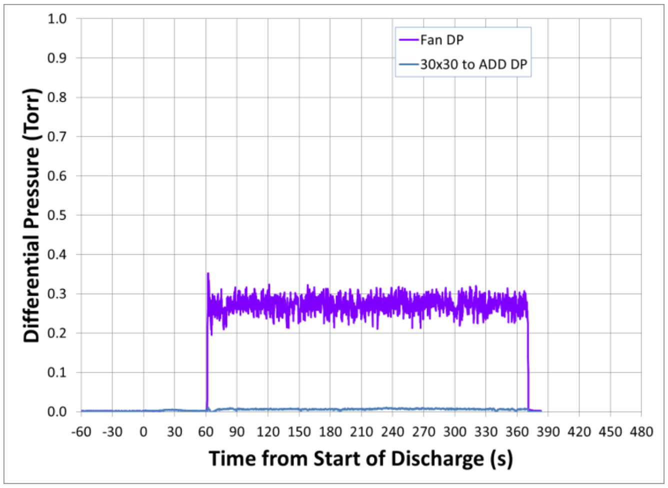
Temperature at Location C



Temperature at 92 in. height above the floor



Refrigerant Concentration



Room and Blower Differential Pressure

Condensate Drain on RTU showing maximum ice build up and condensation escaping through this route. The power cable for the fan motor was routed through the condensate drain.

The candle at location C extinquished 30 seconds after the beginning of the discharge. Candle at location D extinguished at 64 seconds (2 seconds after the blower was started). The candle at location A extinguished at 204 seconds. The candle at location B remained lit throughout the test. The candles were observed to flare up at 20 seconds after the beginning of the discharge.

Mist exiting the supply duct at 62 seconds after the beginning of the discharge. The blower motor had been started 2 seconds prior to this frame. The candle at location D extinguished 2 seconds later.

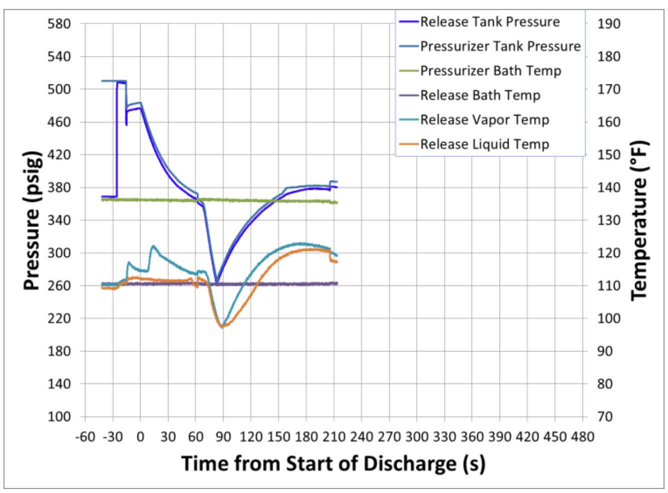
Figure 122 – Data from Kitchen04

4.5.3.4.5. Kitchen05:

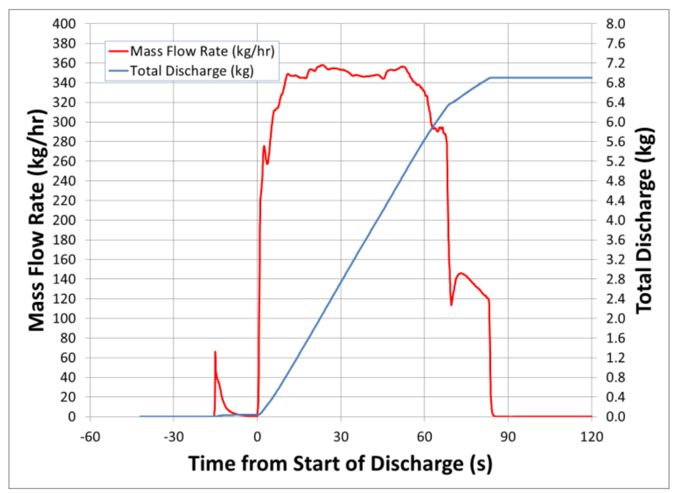
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Mitigation (Blower Energized) time	Ignition Result
R-32	100	6.89	Start of Discharge + 60 seconds	No ignition

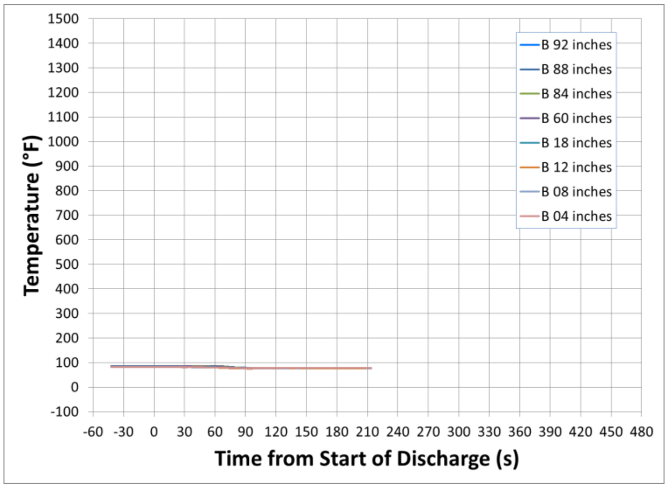
There was no ignition during the test. The candles at locations B and C extinguished before the test began. The candles at locations A and D flared up 20 seconds after the beginning of the discharge. The candle at location D extinguished at 29 seconds after the beginning of the discharge. The electric arc locations were observed have flames about 1 inch long attached to the arc after the blower motor was running for 5 seconds. The candle at location A extinguished 60 seconds after the blower motor was started. Selected data from this test are shown in Figure 123.



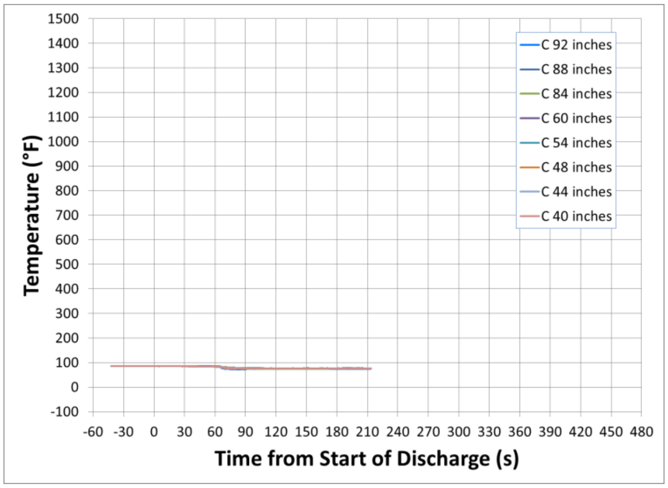
Pressure and Temperature in Pressurizer and Release Tanks



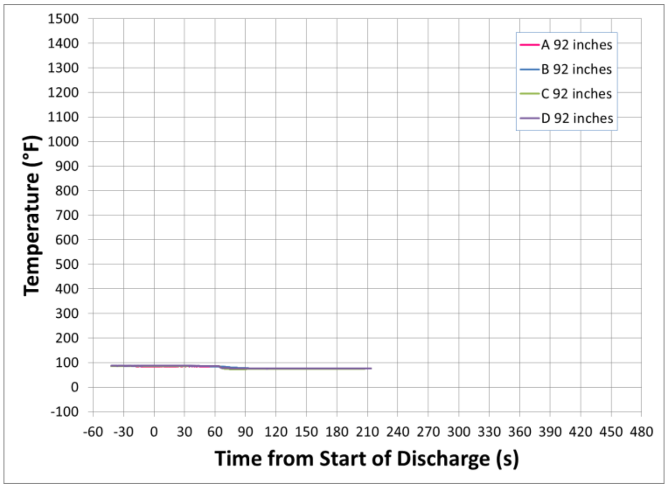
Refrigerant Release Rate



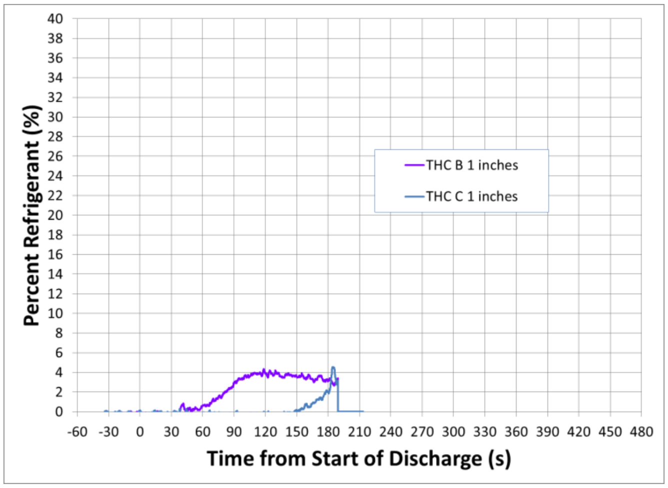
Temperature at Location B



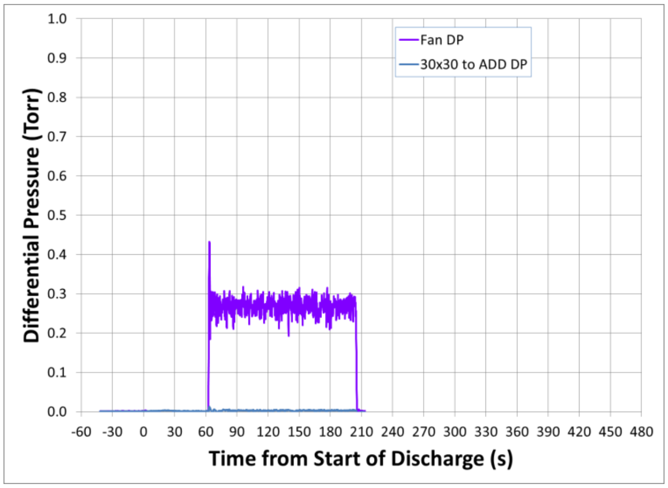
Temperature at Location C



Temperature at 92 in. height above the floor



Refrigerant Concentration



Room and Blower Differential Pressure

Condensate Drain on RTU

This frame shows ice buildup and a substance being ejected. It is not known whether this was ice, refrigerant or a mix of the two. The power cable for the fan motor was routed through the condensate drain.

The candles at location B and C flamed out before the beginning of the test. The candle at Location D flared up at 20 seconds after the beginning of the discharge. This candle extinguished 5 seconds later. The candle at location A extinguished at 204 seconds.

Mist exiting the supply duct at 62 seconds after the beginning of the discharge. The blower motor had been started 2 seconds prior to this frame. Flames about 1 inch in height were observed at the electric arc locations after the blower had been running for 5 seconds.

Figure 123 – Data from Kitchen05

4.5.4. Walk-in Cooler Scenario

The walk-in cooler scenario involved the use of a Heatcraft model LET065BEB2NK6MK evaporator. The test setup for the walk-in cooler is shown in Figure 124, Figure 125, and Figure 126. The dimensions of the walk-in cooler were 12 X 14 X 8 ft. high. Objects representing 6 ft. high shelves were located in the test area.

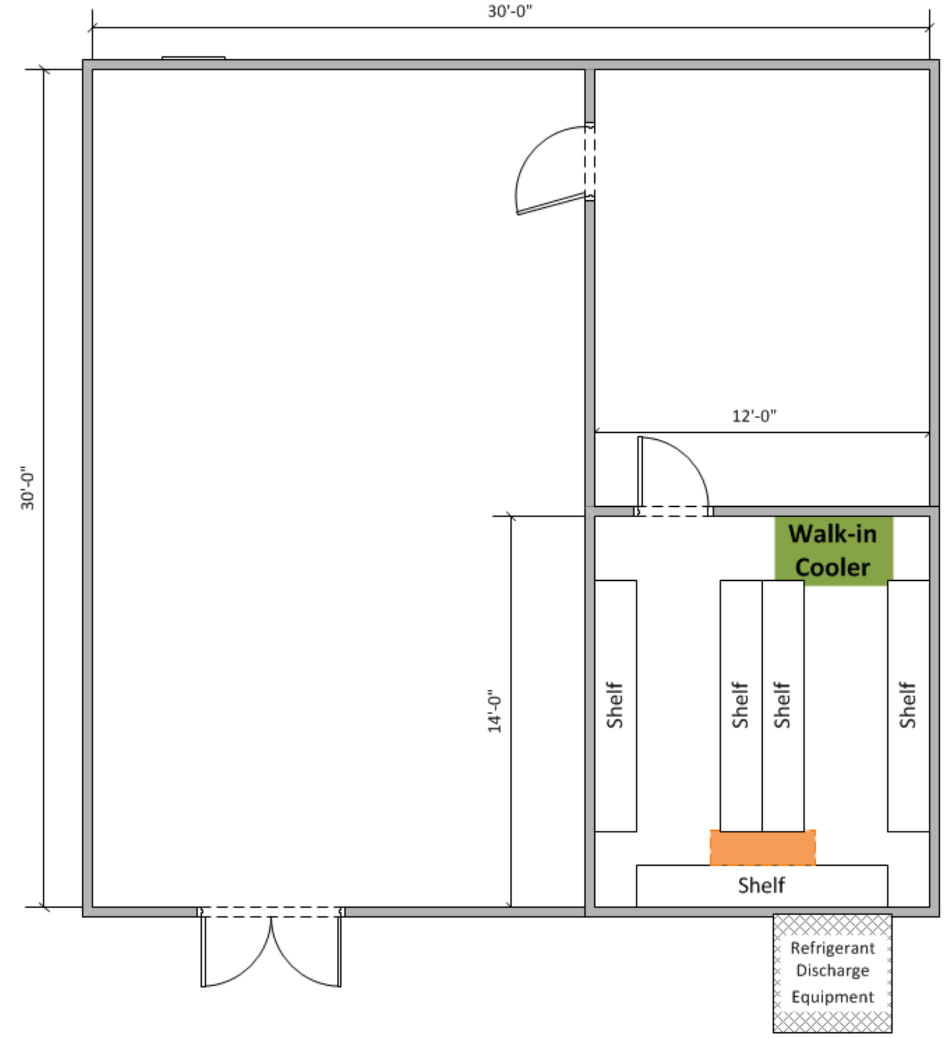


Figure 124 – Walk-in cooler Layout within the 30'x30' test room

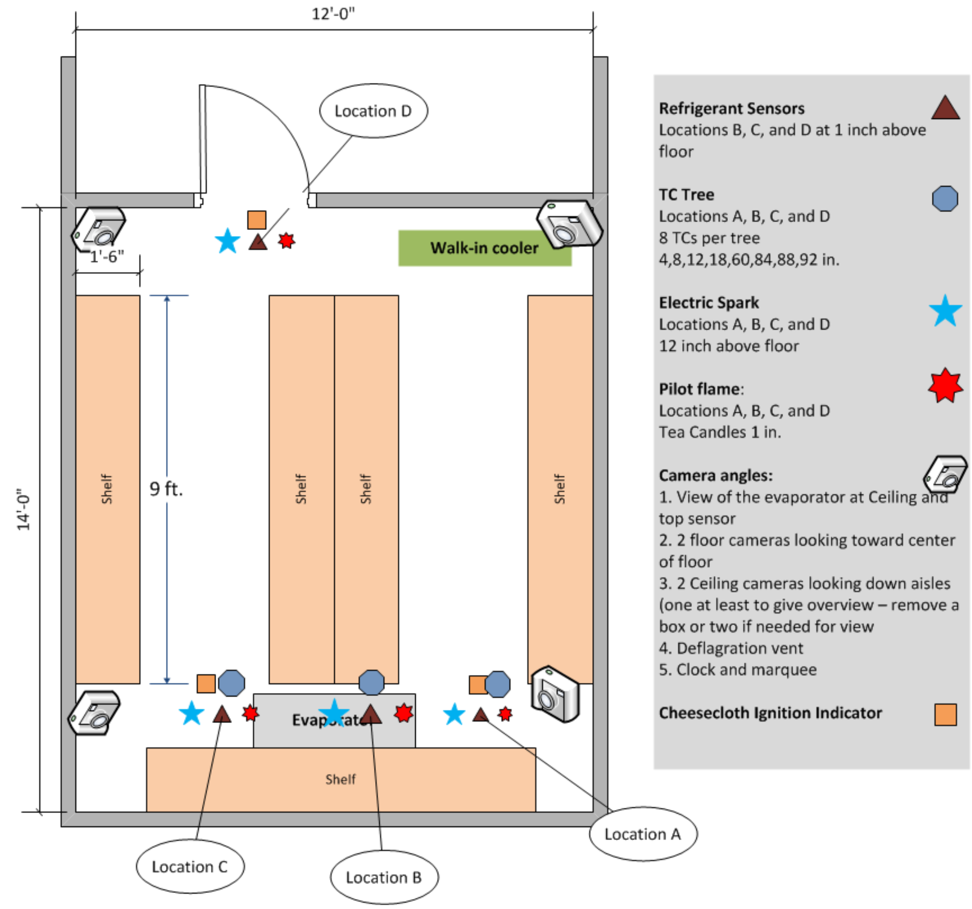


Figure 125 – Larger view of Walk-in cooler detail

Figure 126 - Camera view of evaporator mounting and obstructions

The locations of the instrumentation, and ignition sources were located in clusters at locations A, B, C, and D. The locations relative to the front and right walls are shown in Table 35.

Table 35 – Location of Instrumentation and Ignition Sources

Item	Location	Number	Height above Floor (in.)	Distance from front wall (ft.)	Distance from right wall (ft.)
Refrigerant sensor	C	1	1	2.5	9
	D	1	1	13	9
Thermocouples	A	8	40, 44, 48, 54, 60, 84, 88, 92	2.5	3
	B	8	4, 8, 12, 18, 60, 84, 88, 92	2.5	6
	C	8	40, 44, 48, 54, 60, 84, 88, 92	2.5	9
Pilot flame	A	1	1	2.5	3
	B	1	1	2.5	6
	C	1	1	2.5	9
	D	1	1	13	9
Electric Arc	A	1	12	2.5	3
	B	1	12	2.5	6
	C	1	12	2.5	9
	D	1	12	13	9

4.5.4.1. *Refrigerant Release*

The walk-in cooler scenario involved the use of a ceiling mounted commercial refrigeration unit with the refrigerant leak in the evaporator. The refrigerant release quantities were based on $13\ m^3 \times LFL\ \frac{kg}{m^3}$ (from draft version of IEC 60335-2-89) [14] for R-455A and R-457A. The planned quantities for release were 5.4 kg for R-455A and 2.7 kg for R-457A. The release in all cases was set to 50 g/s through a 3/8 inch diameter copper tube. The length of the tube was approximately 3 meters and was attached to a 1 by 3/8 inch reducer at the exit of the mass flow control valve. Other variables in this scenario included the position of the door (open or closed) and the location of the discharge tube (near a return bend or in the coil face).

The test matrix showing all of these factors is presented in Table 36.

Table 36 – Walk-in Cooler Experimental Matrix

Refrigerant	Test Number	Door Condition	Leak Location	Planned Discharge (kg)	Discharge Rate (g/s)
R-455A	Walkin08	Closed	Return Bend	5.4	50
R-457A	Walkin09	Closed	Return Bend	2.7	50
R-457A	Walkin10	Open	Return Bend	2.7	50
R-455A	Walkin11	Open	Return Bend	5.4	50
R-455A	Walkin12	Closed	Coil Face	5.4	50
R-457A	Walkin13	Closed	Coil Face	2.7	50
R-455A	Walkin14	Open	Coil Face	5.4	50

[14] International Electrotechnical Commission (IEC), 60335-2-89, Household and similar electrical appliances – Safety – Part 2-89: Particular requirements for commercial refrigerating appliances with an incorporated or remote refrigerant unit or compressor,. Developed by IEC Subcommittee 61C, Safety of Refrigeration Appliances for Household and Commercial Use, Working Group 4 Commercial Refrigerating Appliances using more than 150 g of Flammable Refrigerant.

4.5.4.3. Test Procedure

The following procedure was used to initiate each test:

1. Confirm pressurizer and release refrigerant tank pressures and temperatures.
2. Develop vacuum (less than 1mm Hg) in piping connecting the pressure and release tanks as well between the release tank and flow meter.
3. Confirm the walk-in cooler temperature and humidity were at 91±3°F and 70±5% relative humidity.
4. Light the candles, turn on electric arcs, and turn off the lab HVAC and humidity systems.
5. Initiate data acquisition and video capture 1 minute prior to discharging refrigerant.
6. Open the valve between the pressure and release tanks, and hold for 5 seconds.
7. Open the valve between release tank and the flow meter and hold for 5 seconds.
8. Open the control valve to initiate refrigerant discharge through the mass flow meter.
9. Continue to collect data until all flaming has ceased for at least 2 minutes.
10. Vent the test room.

After each test, the test facility was exhausted through UL's smoke abatement system, and the conditions in the facility were monitored with open path gas FT-IR. Staff re-entered the test facility for the next only after the gas FT-IR indicated normal ambient conditions.

4.5.4.4. Summary of Findings – Walk-in Cooler Tests

The location of the discharge influenced ignition results. Tests with the discharge at the return bend forced the refrigerant to leave the unit cooler through the condensate drain and drop to the floor. This direct path to floor level resulted in flammable refrigerant mixtures. In contrast, the discharge through the coil face resulted in turbulent mixing of the refrigerant with air before the cooled mixture dropped to the floor. This indirect path to floor level resulted in less flammable mixtures. The position of the door, open or closed, appeared to have little impact on ignition results.

Figure 127 shows a bar chart of maximum temperature for the seven experiments based on the three factors of: Refrigerant type (R-455A or R-457A), Discharge Location (Coil Face or Return Bend), and Door Position (Closed or Open). The chart shows that ignition of the R-455A discharge lead to the highest temperatures, but only from the return bend. There was no ignition for either refrigerant when discharged from the coil face.

There was a small effect on maximum temperature depending on whether the walk-in door was open or closed. The videos show that ignition occurred only at locations A, B, or C. No ignition occurred at location D (near the walk-in door).

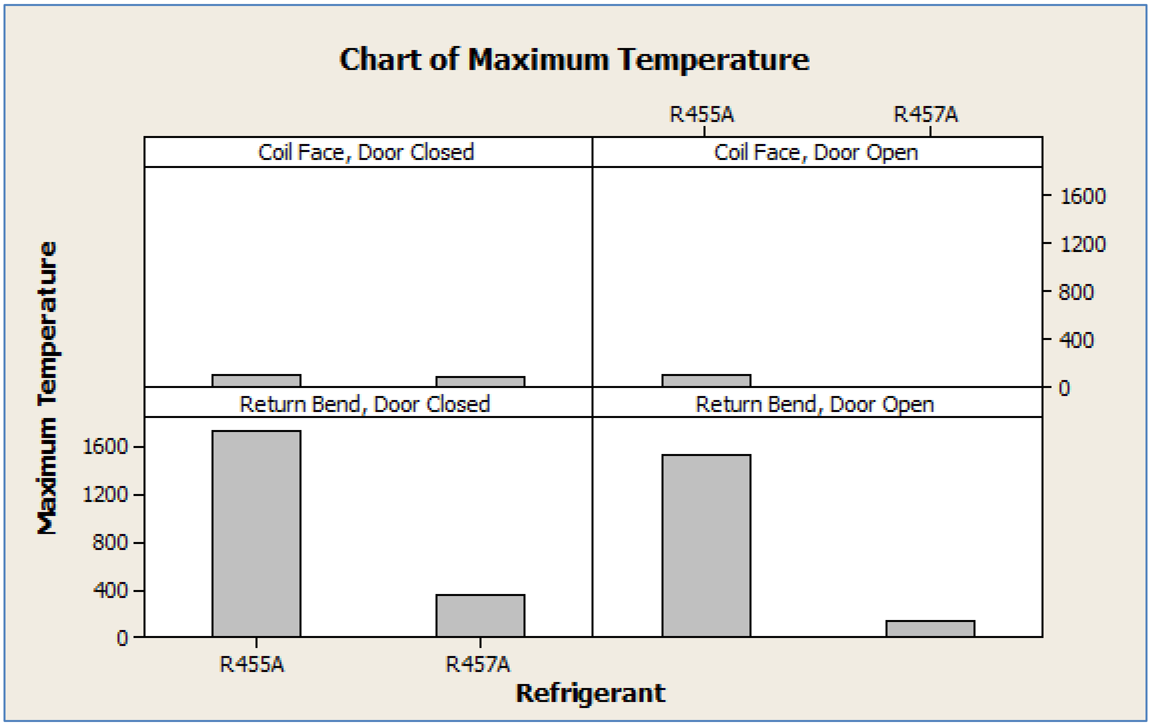


Figure 127 – Chart of Maximum Temperature versus Discharge Location and Door Position

As with other task 2 experiments, the tea candles were sometimes extinguished by either high local refrigerant concentration or the combination of the cooling effect and movement of air. This is especially true at Location C. In some tests, the videos show these candles being extinguished and later re-ignited by the burning refrigerant-air mixture.

4.5.4.5. Results

A summary of test results are presented in Table 37 and Table 38.

Table 37 – Walk-in Scenario Discharge Mass, Rate, and Maximum Concentration

Refrigerant	Test Number	Measured Discharge (kg)	Planned Discharge (kg)	Measured Rate (g/s)	Maximum Refrigerant Concentration Measured (%)
R-455A	Walkin08	5.25	5.4	46.3	10.2
R-457A	Walkin09	2.84	2.7	48.7	6.7
R-457A	Walkin10	2.91	2.7	45.6	7.2
R-455A	Walkin11	5.25	5.4	38.9	8.3
R-455A	Walkin12	4.95	5.4	36.6	8.6
R-457A	Walkin13	3.06	2.7	46.9	4.4
R-455A	Walkin14	5.20	5.4	43.9	5.4

Table 38 – Walk-in Scenario Summary

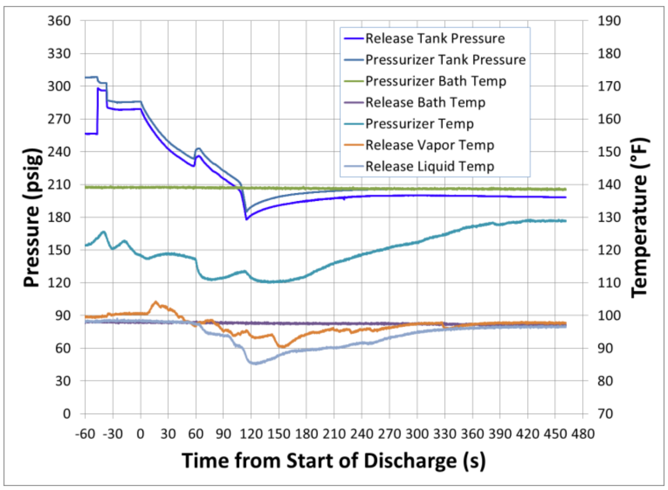
Refrigerant	Test Number	Door Condition	Leak Location	Max Pressure (mmHg)	Max Temperature and Location (°F) /Location	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	Result
R-455A	Walkin08	Closed	Return Bend	0.00	1735 / C88	1588	1363	Ignition
R-457A	Walkin09	Closed	Return Bend	0.01	354 / C04	180	151	Local Ignition
R-457A	Walkin10	Open	Return Bend	0.01	142 / C04	114	110	Local Ignition
R-455A	Walkin11	Open	Return Bend	0.01	1541 / A92	1541	1436	Ignition
R-455A	Walkin12	Closed	Coil Face	0.00	95 / A04	89	88	Local Ignition
R-457A	Walkin13	Closed	Coil Face	0.00	92 / C60	88	87	No Ignition
R-455A	Walkin14	Open	Coil Face	0.00	100 / C04	93	91	No Ignition

4.5.4.5.1. *WALKIN08:*

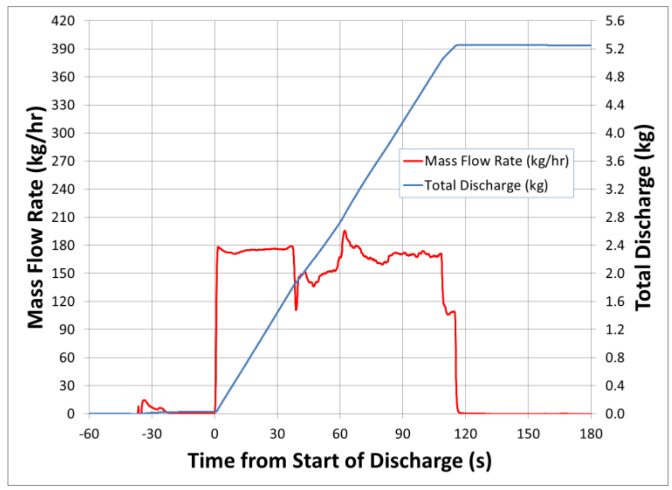
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Door Position	Leak Location	Ignition Result
R-455A	50	5.4	Closed	Return Bend	Ignition

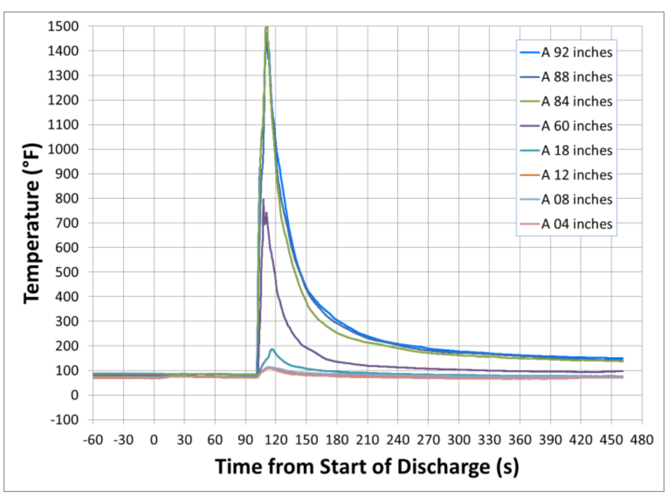
In order to prevent a room-deforming overpressure, the door latch was disabled allowing the door to serve as a deflagration vent. This door was forced open during the test at the time of the first large ignition. Selected data from this test are shown in Figure 128.



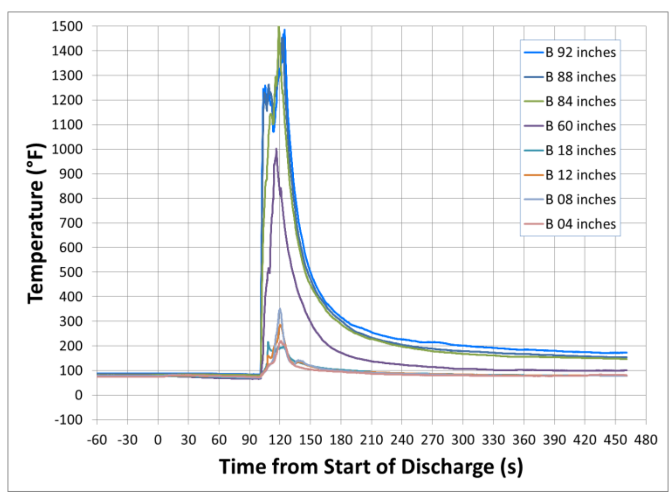
Pressure and Temperature in Pressurizer and Release Tanks



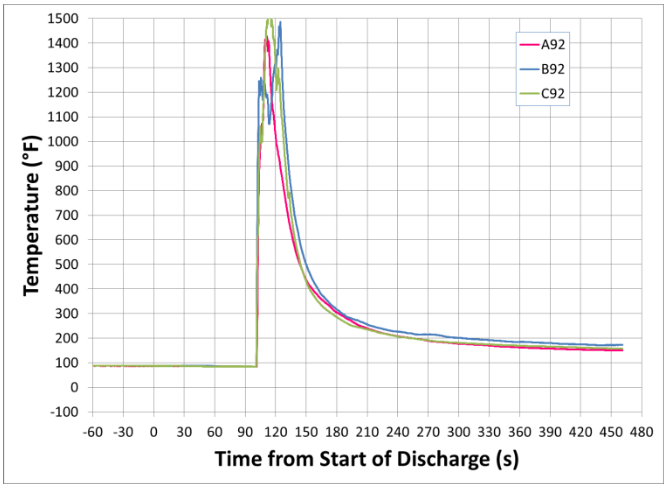
Refrigerant Release Rate



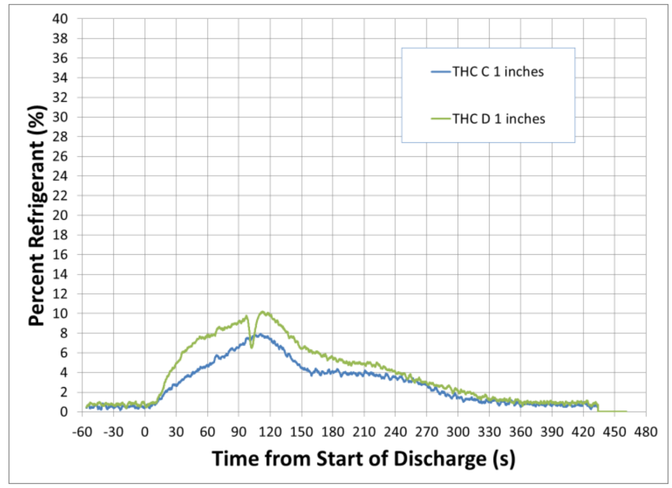
Temperature at Location A



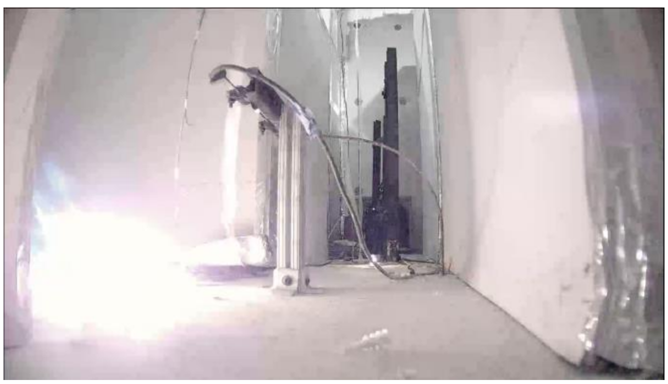
Temperature at Location B



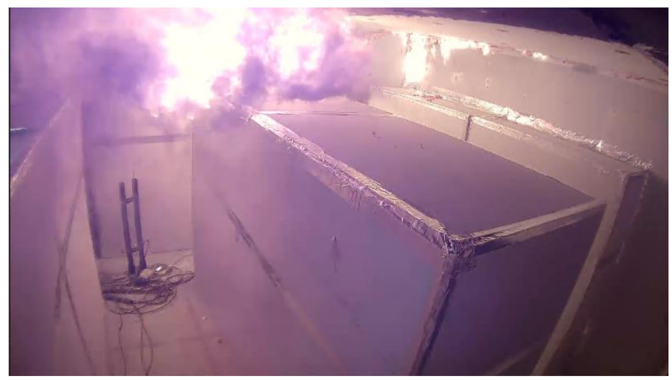
Temperature at 92 in. height above the floor



Refrigerant Concentration



Floor level view at 10 seconds after the start of the discharge. Localized flaming occurred at the electric arc locations.



Ceiling level view of flames at ceiling height 105 seconds after that start of the discharge.

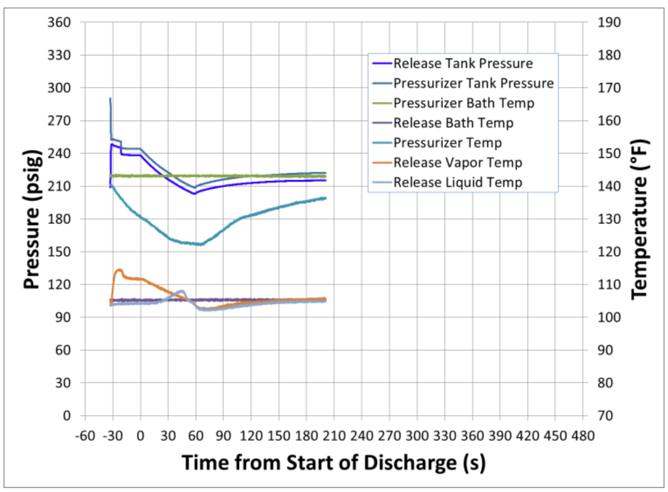
Figure 128 – Data from WALKIN08

4.5.4.5.2. *WALKIN09:*

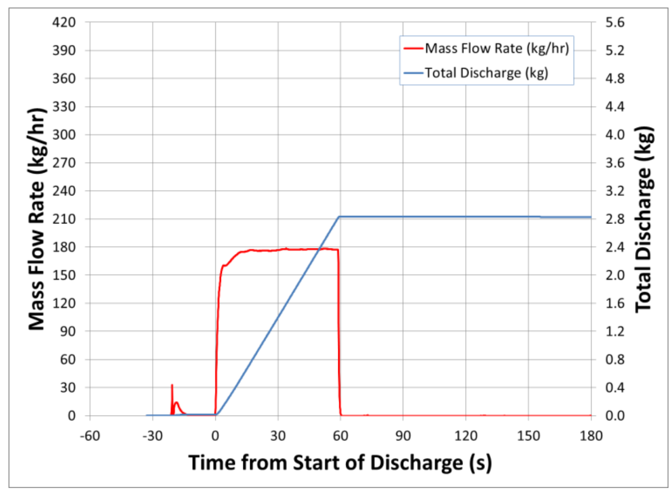
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Door Position	Leak Location	Ignition Result
R-457A	50	2.7	Closed	Return Bend	Ignition localized to igniters

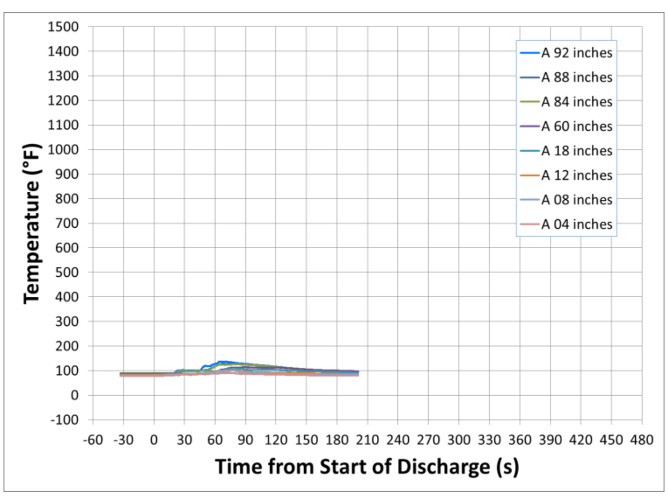
In order to prevent a room-deforming overpressure, the door latch was disabled allowing the door to serve as a deflagration vent. This door was forced open during the test at the time of the first large ignition. Selected data from this test are shown in Figure 129.



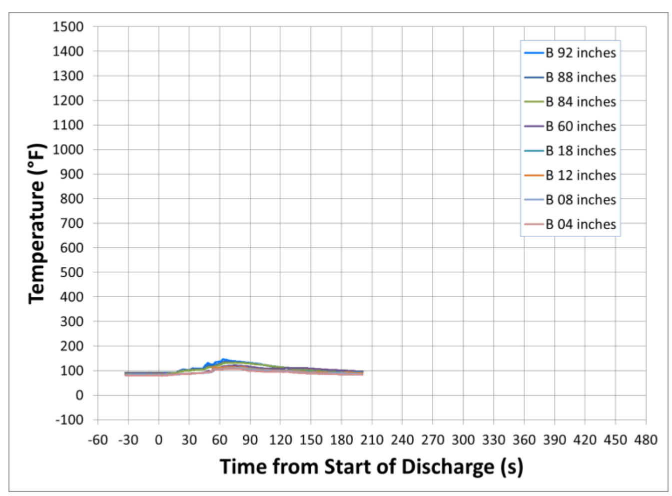
Pressure and Temperature in Pressurizer and Release Tanks



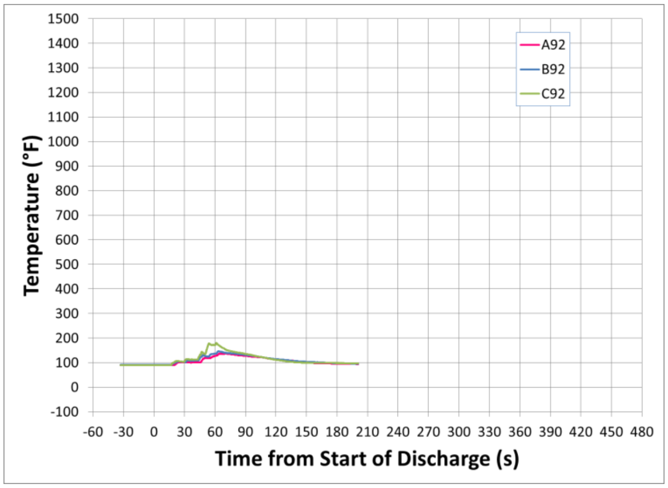
Refrigerant Release Rate



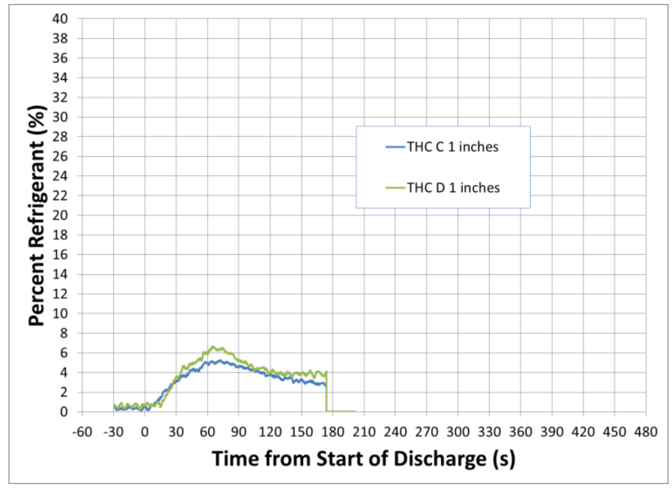
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

Floor level view at of initial flaming at 13 seconds after the start of the discharge. Localized flaming occurred at the electric arc locations.

Floor level view at 21 seconds after the start of the discharge. Door was forced open by over pressure 4 seconds later.

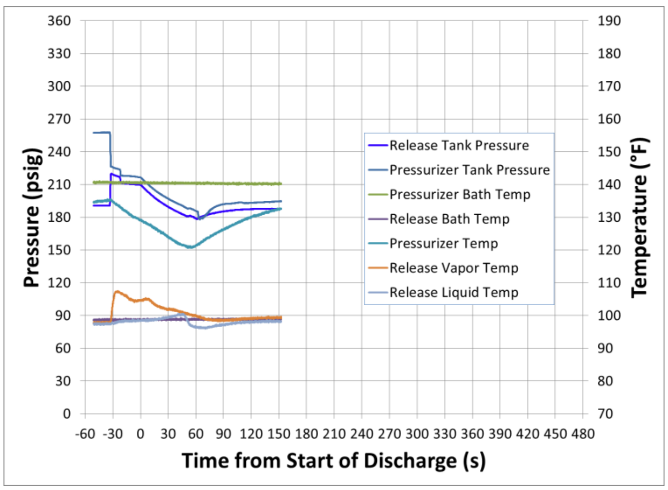
Figure 129 – Data from WALKIN09

4.5.4.5.3. WALKIN10:

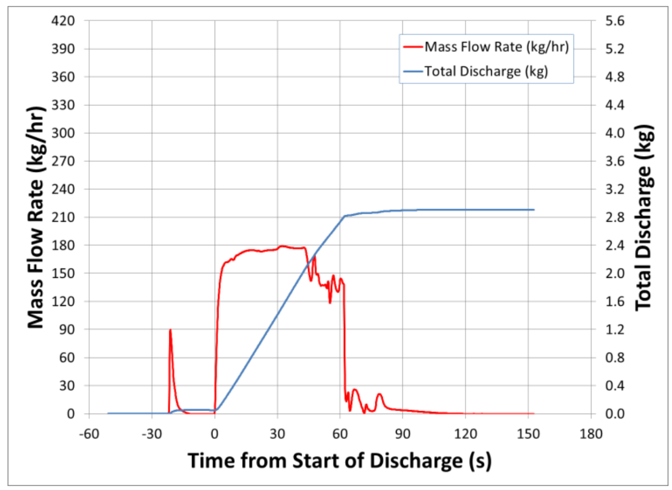
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Door Position	Leak Location	Ignition Result
R-457A	50	2.7	Open	Return Bend	Ignition localized to igniters

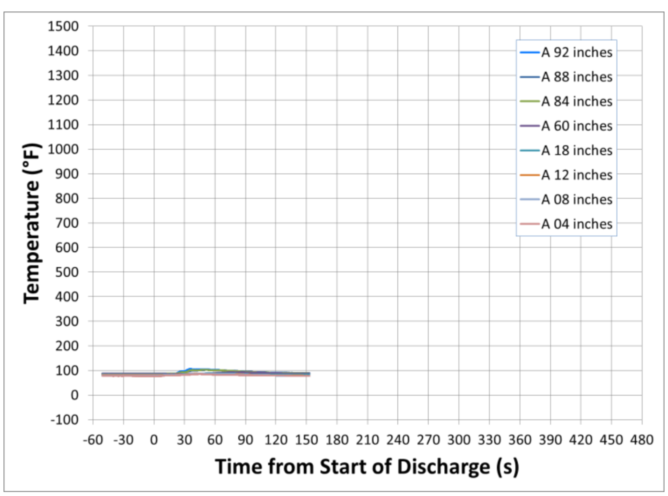
The door to the walk-in cooler was left open in this test compare with the door-closed test in the Walkin09 test. Selected data from this test are shown in Figure 130.



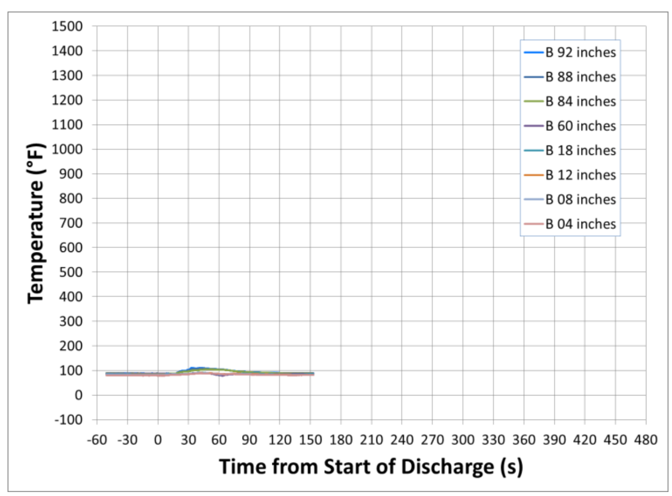
Pressure and Temperature in Pressurizer and Release Tanks



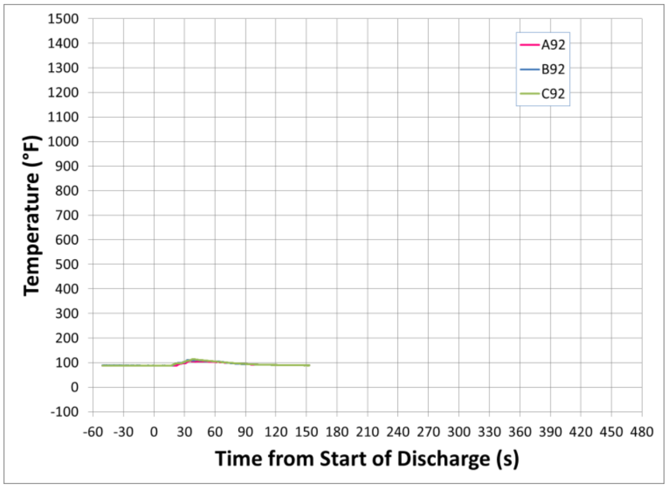
Refrigerant Release Rate



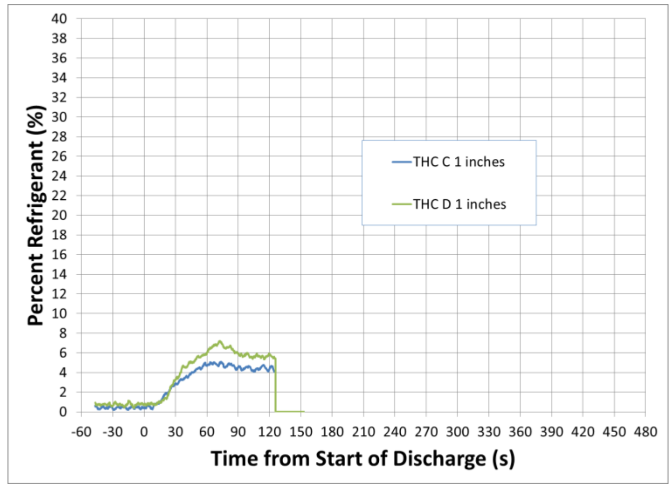
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

Floor level view at of initial flaming at 11 seconds after the start of the discharge. Localized flaming occurred at the electric arc locations.

Floor level view at 30 seconds after the start of the discharge. Flames of this size were typical for a period of 27 seconds.

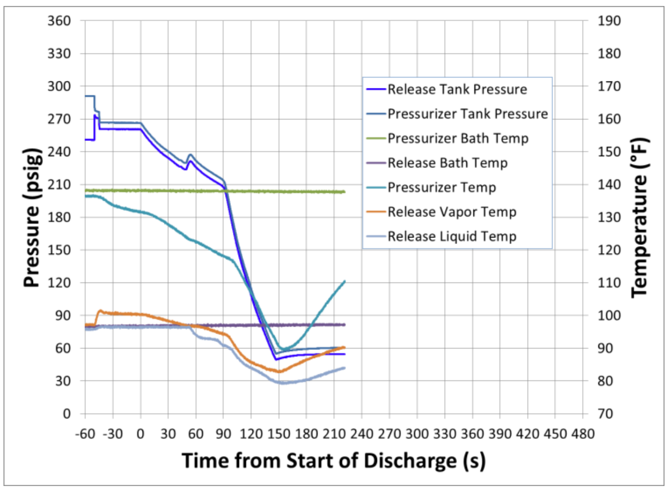
Figure 130 – Data from WALKIN10

4.5.4.5.4. WALKIN11:

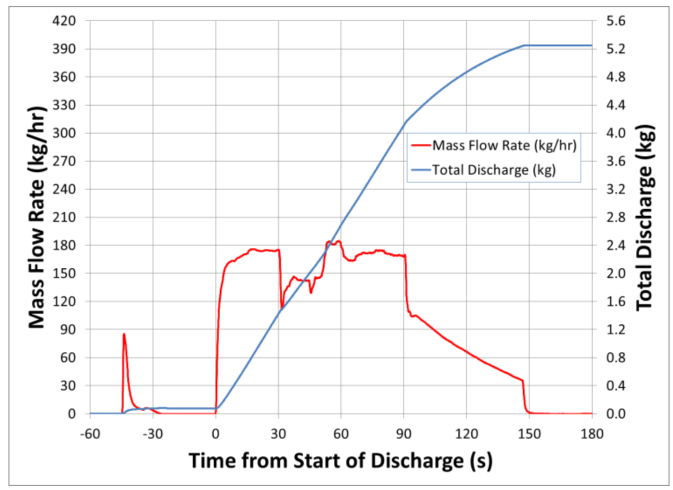
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Door Position	Leak Location	Ignition Result
R-455A	50	5.4	Open	Return Bend	Ignition

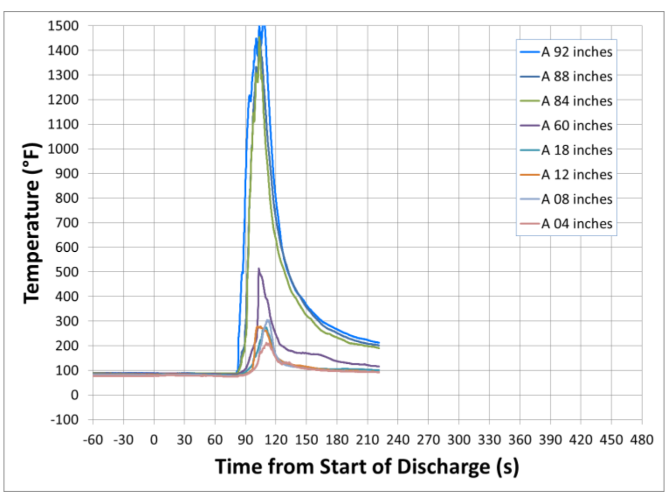
The door to the walk-in cooler was left open in this test compare with the door-closed test in the Walkin09 test. Selected data from this test are shown in Figure 131.



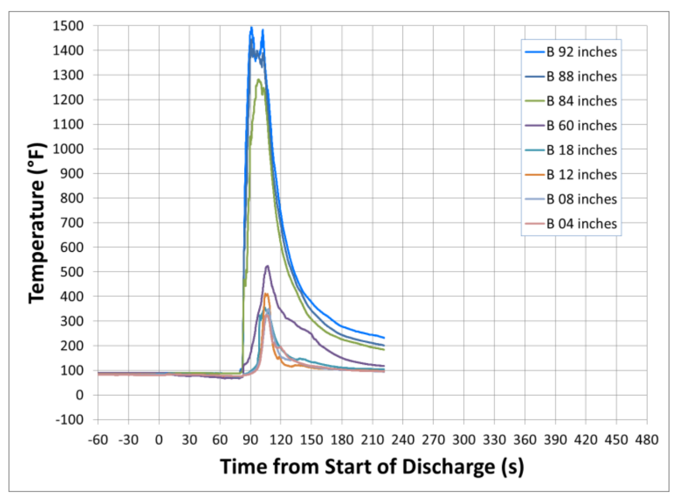
Pressure and Temperature in Pressurizer and Release Tanks



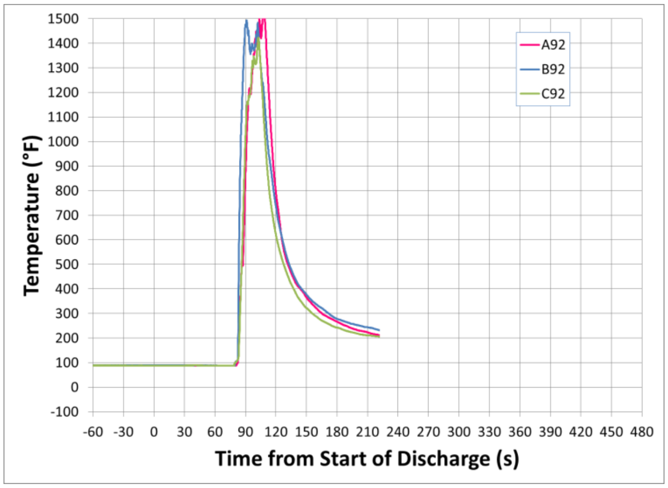
Refrigerant Release Rate



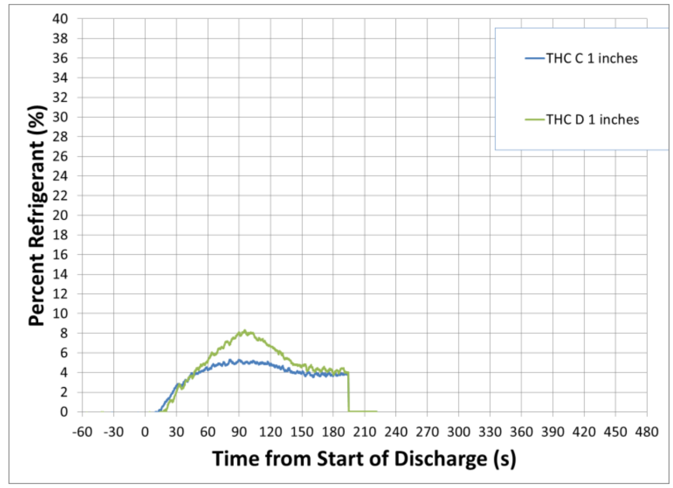
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

Floor level view of the start of ignition at 18 seconds after the start of the discharge.

Ceiling level view of flames at ceiling height 93 seconds after that start of the discharge. The ceiling is obscured by smoke.

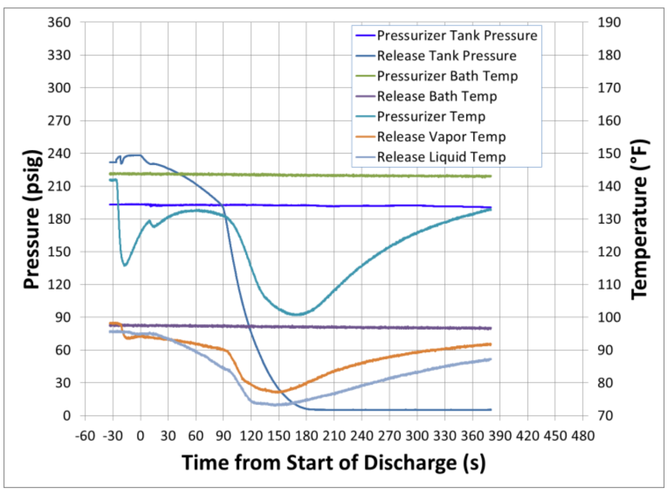
Figure 131 – Data from WALKIN11

4.5.4.5.5. WALKIN12:

The test parameters for this test were as follows:

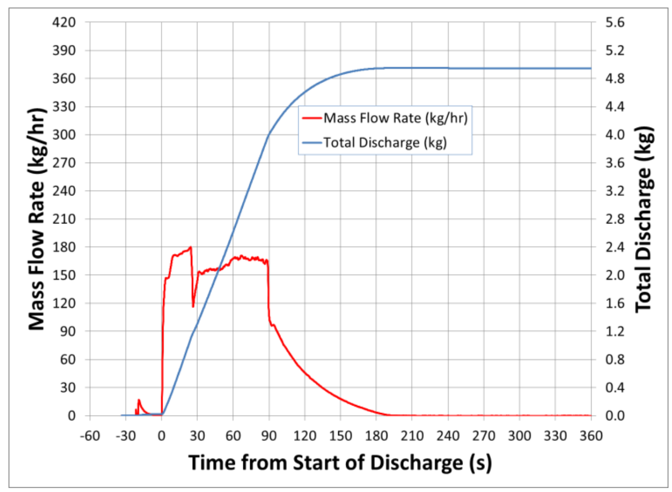
Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Door Position	Leak Location	Ignition Result
R-455A	50	5.4	Closed	Coil Face	Ignition localized to igniters

In this test and the following two tests, the discharge locations was moved to the center of the coil face. The orientation of the discharge tube directed the discharge horizontally at the level of the unit cooler. The door to the walk-in cooler was closed. Selected data from this test are shown in Figure 132.



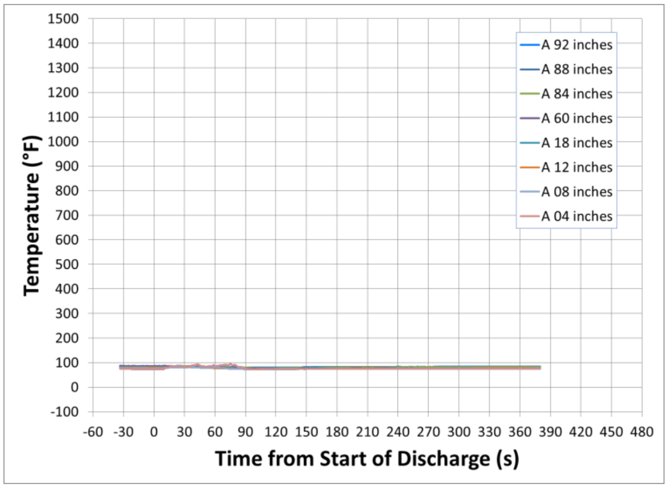
Pressure and Temperature in Pressurizer and Release Tanks

The pressure transmitter on the Pressurizer Tank was accidentally isolated during this test.

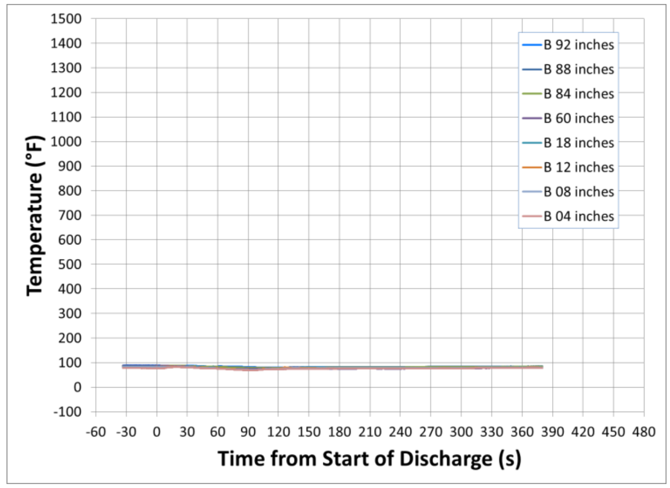


Refrigerant Release Rate

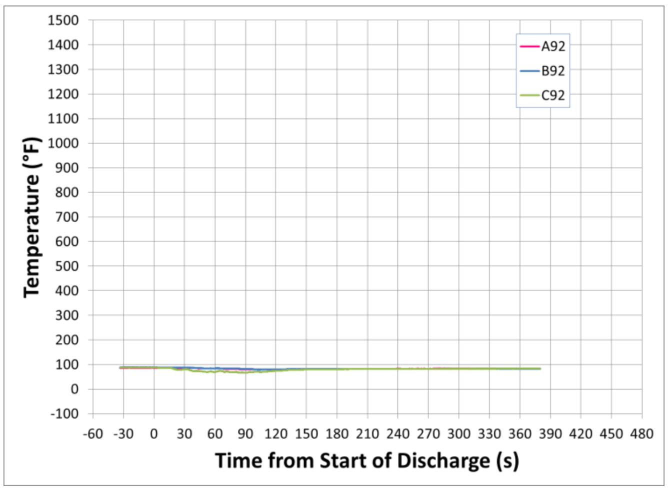
At 90 seconds the discharge from the tanks transitioned into vapor release. Low pressure prevented achievement of the full 5.2 kg release.



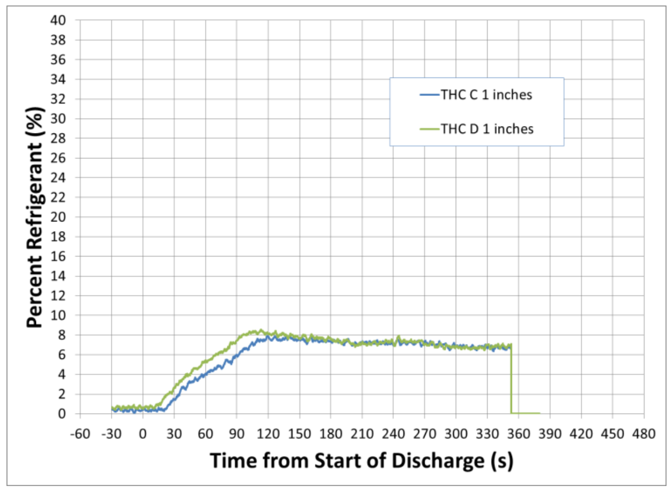
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

	
Ceiling camera view of the discharge showing the condensation cloud at the ceiling level.	Floor camera view showing ignition at location C, 88 seconds after the start of the discharge.

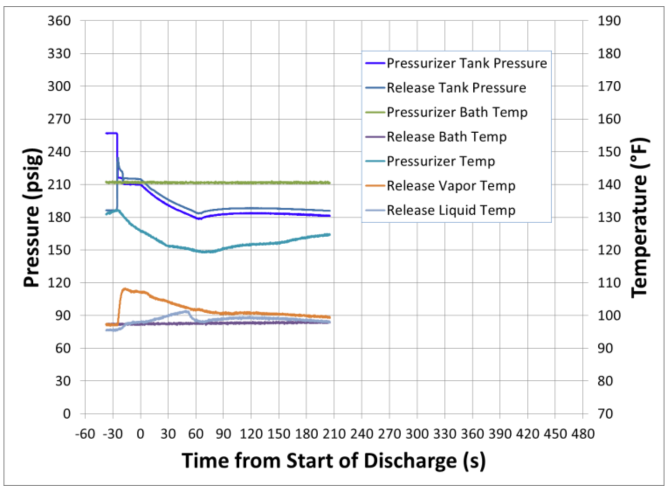
Figure 132 – Data from WALKIN12

4.5.4.5.6. *WALKIN13:*

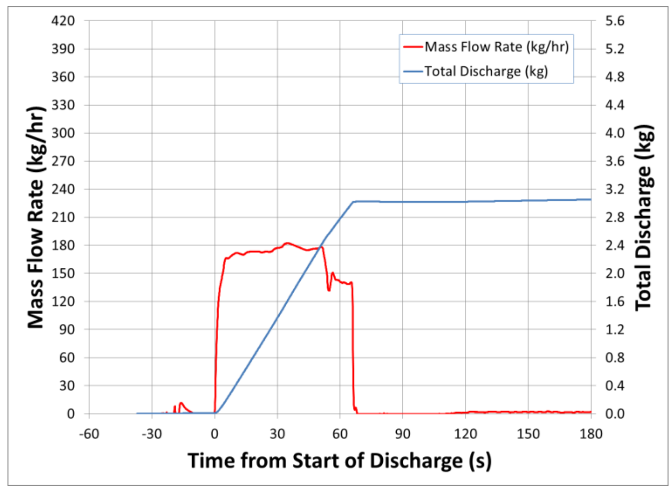
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Door Position	Leak Location	Ignition Result
R-457A	50	2.7	Closed	Coil Face	No Ignition

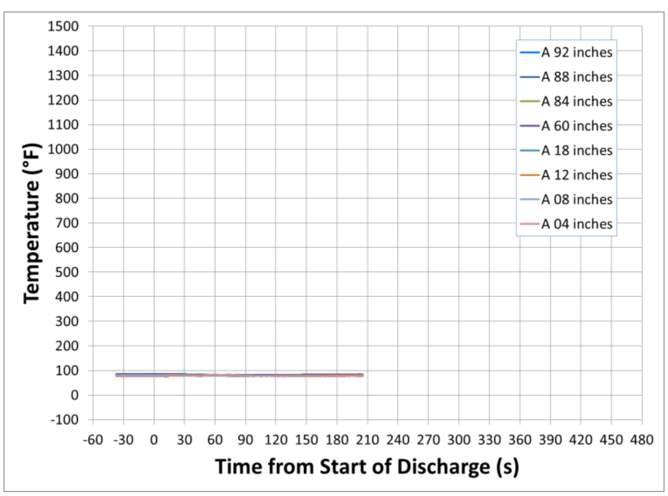
The release of R-457A at the coil face resulted in no ignition. There was a small amount of flaring at location C. Selected data from this test are shown in Figure 133.



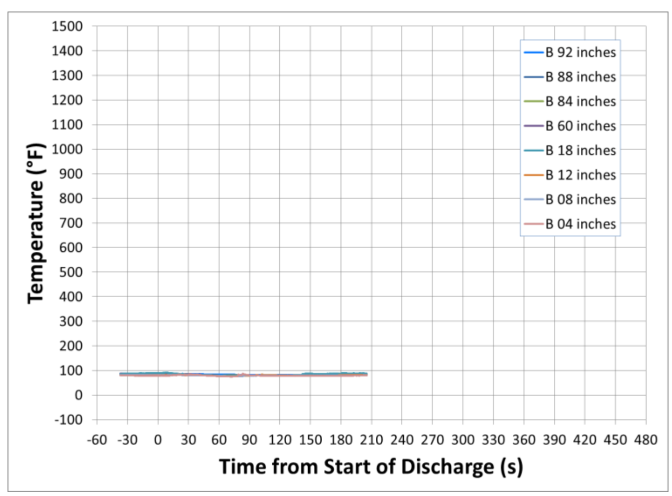
Pressure and Temperature in Pressurizer and Release Tanks



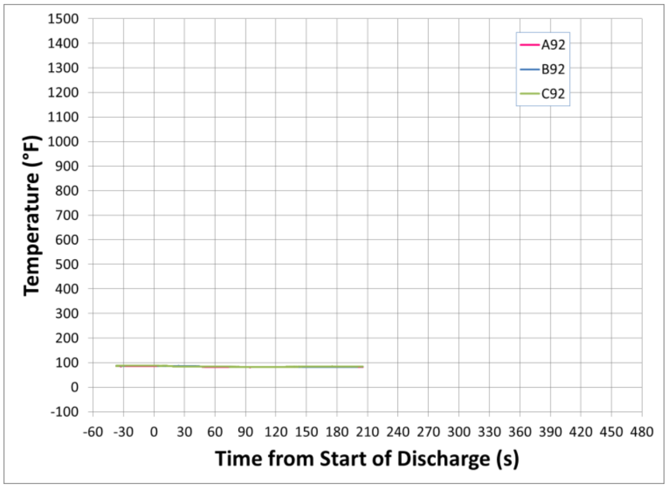
Refrigerant Release Rate



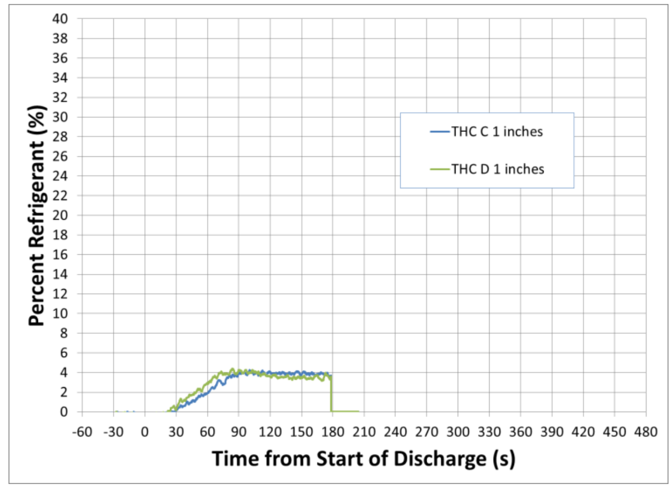
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

Ceiling camera view of the discharge showing the condensation cloud at the ceiling level.

Floor camera view showing flaring at the candles and electric arc at location C.

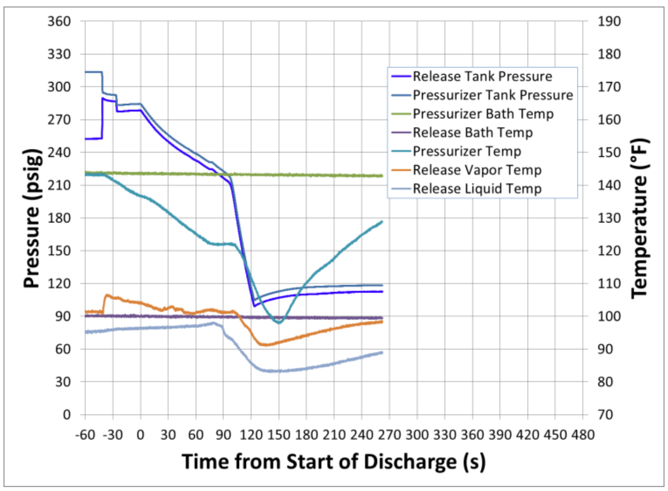
Figure 133 – Data from WALKIN13

4.5.4.5.7. WALKIN14:

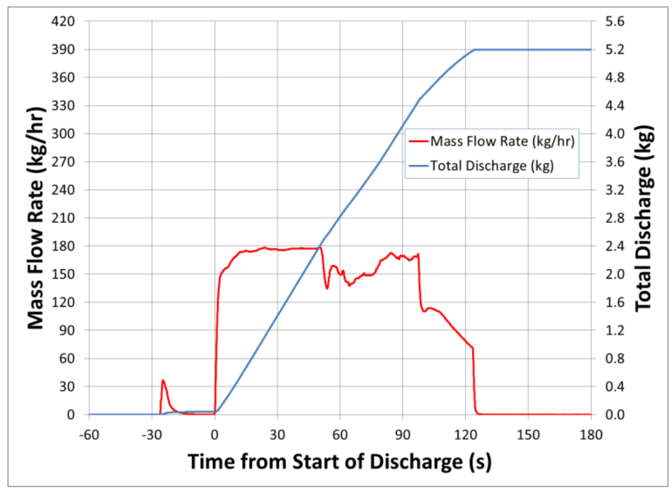
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Planned Discharge (kg)	Door Position	Leak Location	Ignition Result
R-455A	50	5.4	Open	Coil Face	No Ignition

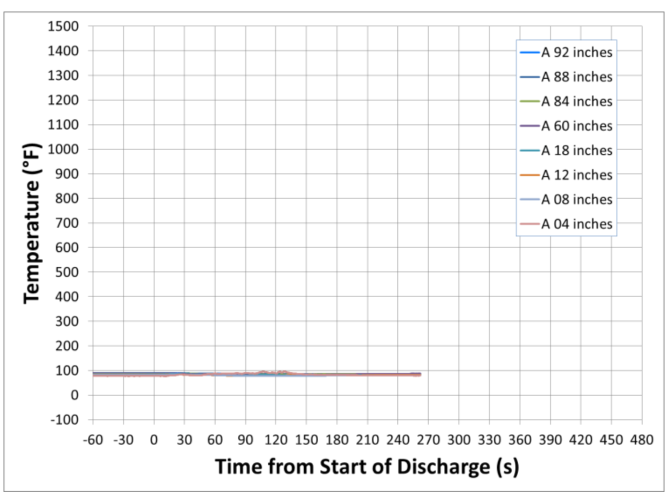
This test is a repeat of the R-455A test in Walkin12 with the exception that the door to the walk-in had been left open. An additional kilogram was added to the pressurizer and release tanks in order to prevent the low pressure seen at the end of the Walkin12 test. Selected data from this test are shown in Figure 134.



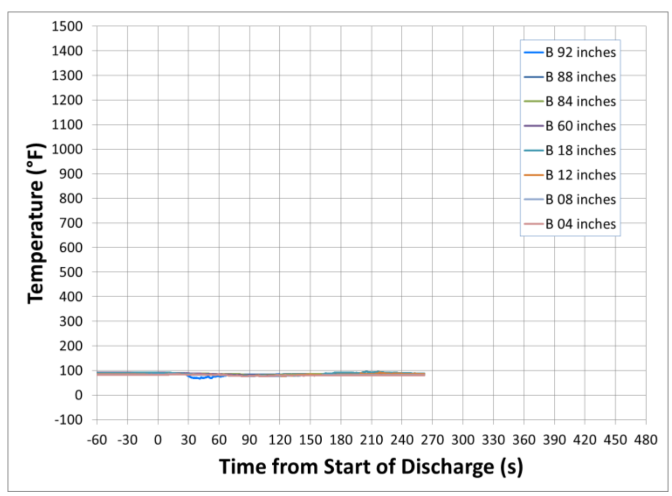
Pressure and Temperature in Pressurizer and Release Tanks



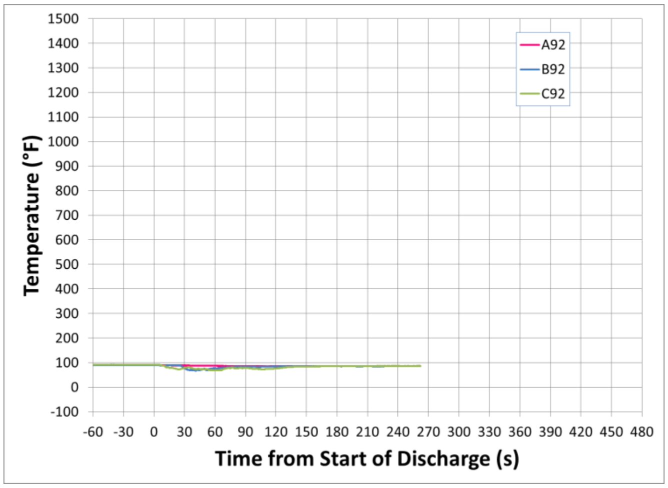
Refrigerant Release Rate



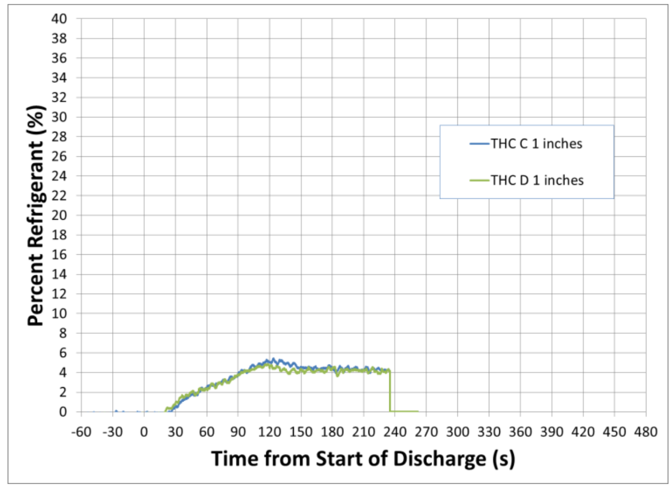
Temperature at Location A



Temperature at Location B

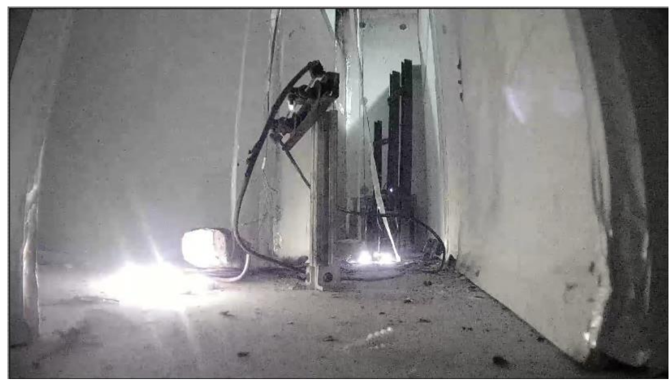


Temperature at 92 in. height above the floor



Refrigerant Concentration

Ceiling camera view of the discharge showing the condensation cloud at the ceiling level.



Floor camera view showing flaring at the candles and electric arc at location C and candles at location B.

Figure 134 – Data from WALKIN14

4.6. Residential Scenarios

4.6.1. Residential A/C Application

The residential A/C application test scenario involved a HVAC unit located in a 24ft. - 2 in. x 30 ft. x 8-ft. (7.4m x 9.3m x 2.4m) high residential arrangement with the air conditioning unit located in an 8 x 4 x 8-ft. (2.4m x 1.2m x 2.4m) high closet. The test setup is shown in Figure 135.

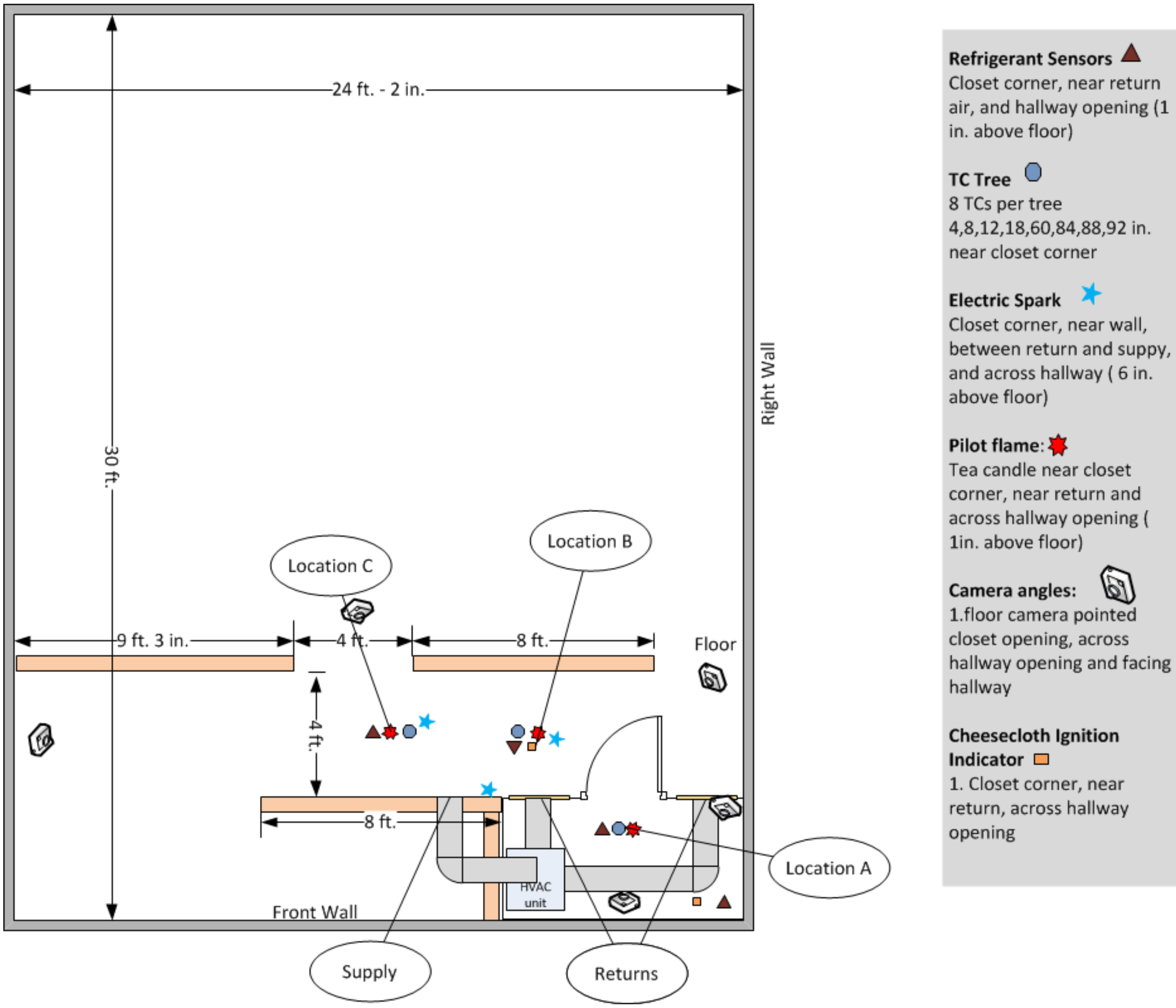


Figure 135 – Residential Scenario Test Setup

The test was configured to represent either a leak in the A-coil or a servicing error outside of the indoor unit. Ignition sources consisting of an electric arc and a candle flame were positioned in proximity of the refrigerant release location.

The air conditioning unit was ducted with return air from the bottom and conditioned air ducted to the hallway using a 16 inch duct. The closet had two return air grills at the bottom that were ducted to the air conditioning unit. The supply air duct was located at 2.2m height. A photograph of the return and supply air ducts connecting to the air conditioning unit is shown in Figure 136.

Return air duct connection to grills in Hallway

Supply Air Duct to Hallway

Figure 136 – Return Air and Supply Ducts Air connecting to Air Conditioning Unit

The locations of the instrumentation, and ignition sources were located in clusters at locations A, B, and C. The locations relative to the front and right walls are shown in Table 39.

Table 39 – Location of Instrumentation and Ignition Sources (Residential A/C)

Item	Location	Number	Height above Floor (in.)	Distance from front wall (ft.)	Distance from right wall (ft.)
Refrigerant sensor	A	2	1	2.5	4.0
	B	1	1	6.5	7.0
	C	1	1	6.5	12.0
Thermocouples	A	8	4, 8, 12, 18, 60, 84, 88, 92	2.5	4.0
	B	8	4, 8, 12, 18, 60, 84, 88, 92	6.5	7.0
	C	8	4, 8, 12, 18, 60, 84, 88, 92	6.5	12.0
Pilot flame	A	1	1	2.5	4.0
	B	1	1	6.5	7.0
	C	1	1	6.5	12.0
Electric arc igniter	A	2	6	3.0	3.0
	B	1	6	6.5	7.0
	C	1	6	6.5	12.0
	Near return	1	6	4.5	8.5

4.6.1.1. Refrigerant Release

Two charge levels were used for each tested refrigerant. First, the m_1 charge per a proposed revision to IEC 60335-2-40 ($6\ m^3 \times LFL\ \frac{kg}{m^3}$) was selected for testing. This is the maximum allowable charge with which mitigation is not required for any type of equipment covered by the standard. Then, a higher charge level than m_1 charge was tested following the defined mitigation requirement per the proposed standard. The maximum allowable charge (M_{max}) for the tested room was calculated per GG10 of the proposed standard to be 22.15kg for R-32 and 22.74 kg for R-452B. The M_{max} was not used because it was deemed excessive for the size of the room. The representative charge quantities for that size system and space were determined by making adjustments to the standard R-410A charge (assuming total line set length of 100 feet when installed). According to manufacturers' input, a properly sized R-410A unit for the tested space typically needs 5.24 kg with 100 ft line set. To achieve the same capacity, the PMS committee estimated the R-32 and R-452B systems would have 27% and 20% charge reductions to the R-410A system respectively. Therefore, the charge quantities selected for testing were 3.83 kg for R-32 and 4.20kg for R-452B.

The leakage in the A-coil scenario was conducted with refrigerant only (no oil) at a release rate of 50 g/s.

The servicing error tests, performed with lubricating oil had an initial release rate of 66 g/s. This rate reduced as the pressure in the delivery cylinder dropped. In all the tests, the refrigerant as well as refrigerant-oil mixture was supplied through a 5/16 inch tube. The length of the tube was approximately 3 meters and was attached to a 1 by 5/16 inch reducer at the exit of the mass flow control valve.

It may be noted that the servicing error tests used a release from the bottom of the release tank. In a field installed split system, the system would be shut down and any release might begin as a liquid release but quickly transition to a vapor release. Therefore, the mass rate of discharge in a field installed system would decay with time from the start of the leak.

For the A-coil refrigerant leakage tests, the refrigerant was released at the return bend near the A-Coil within the HVAC unit. For servicing error tests, the leakage was located at outside the HVAC indoor unit.

The matrix of experiments is presented in Table 40.

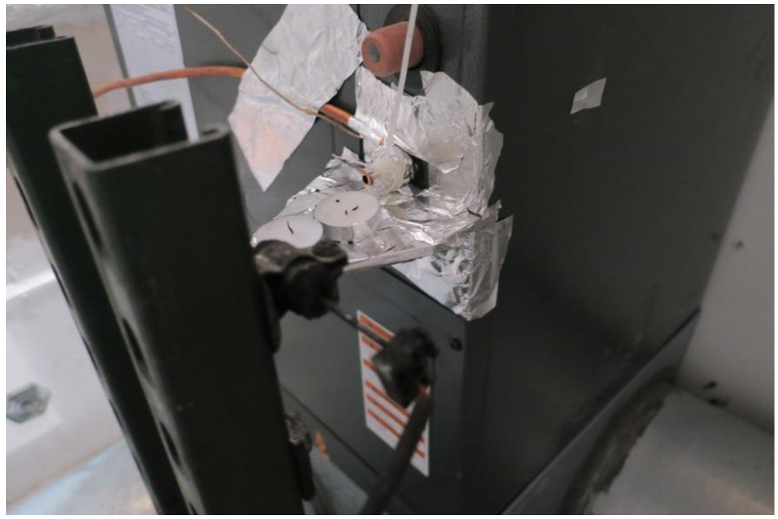
Table 40 – Residential A/C Experimental Matrix

Test ID	Refrigerant	Release Rate (g/s)	Scenario	Mitigation Method	Release Quantity (kg) [1]
Res02	R-32	50	Leakage in A-Coil	Blower in HVAC started 30s after refrigerant release is initiated. If ignition occurs, conduct the test with blower started 15s after release.	3.83
Res03	R-452B	50	Leakage in A-Coil	Blower in HVAC started 30s after release is initiated. If ignition occurs, conduct the test with return air started 15s after release.	4.20
Res04	R-32	50	Leakage in A-Coil	No mitigation	1.80
Res05	R-452B	50	Leakage in A-Coil	No mitigation	1.85
Res06	R-410A + 30g lubricating oil	66 g/s initial with natural pressure decay	Servicing error	No mitigation	1.80
Res07	R-32 + 30g lubricating oil	66 g/s initial with natural pressure decay	Servicing error	No mitigation	1.80
Res08	R-452B + 30g lubricating oil	66 g/s initial with natural pressure decay	Servicing error	No mitigation	1.85

Note: [1] M_{max} quantity for this size room was calculated to be 22.15 kg for R-32; and 22.74 kg for R-452B. These quantities were not used as they were considered excessive by the AHRTI PMS.

Photographs of the refrigerant release locations are shown in Figure 137.

Refrigerant release location for leakage in A-Coil Scenario



Refrigerant release location for service error scenario

Figure 137 – Refrigerant Release Location for Residential A/C Scenarios

The tests were conducted with the test room temperature of 91 ± 3 °F; and humidity of 70 ± 5% RH.

4.6.1.2. Test Procedure

The following procedure was used to initiate each test:

1. Confirm pressure and release refrigerant tank pressure and temperatures.
2. Confirm the test room temperature and humidity.
3. Light the candles and turn off the lab HVAC and humidity systems.
4. Initiate data acquisition and video capture 1 minute prior to discharging refrigerant.
5. Develop vacuum (less than 1mm Hg) in piping connecting the pressure and release tanks as well between the release tank and flow meter (procedure used for leakage in A-coil scenario; a pressurizer tank was not used in serving error scenario).
6. Open the valve between the pressure and release tanks, and hold for 5 seconds (procedure used for leakage in A-coil scenario; a pressurizer tank was not used in serving error scenario); open the valve between release tank and the flow meter and hold for 5 seconds.
7. Energize the solenoid valves to enable refrigerant discharge.
8. Open the control valve to initiate refrigerant discharge through the mass flow meter.
9. Start return air blower in the HVAC unit 30s after refrigerant flow is initiated (for leakage in A-Coil scenario).

After each test, the test facility was exhausted through UL's smoke abatement system, and the conditions in the facility were monitored with open path gas FT-IR. Staff re-entered the test facility only after the gas FT-IR indicated normal ambient conditions.

4.6.1.3. Summary of Findings – Residential Applications

4.6.1.3.1. Discussion of Results - Leakage in A-Coil Scenario

In the tests with and without mitigation, both the R-32 and R-452B refrigerants ignited in the hallway in 12 seconds in proximity to the return grill where pilot flame and electric arc sources were located. While most of the flaming occurred in proximity to the leaked refrigerants near the return grill, there was some spread of flame along the hallway.

The mitigation (starting the blower fan in the HVAC unit) appeared to reduce the time for flaming in the hallway. However, the flames were drawn into the HVAC unit through the return grill and flaming was observed within the unit. Smoke was observed emitting from the supply grill as the flames were drawn into the return grill.

Comparing the leakage rates between the A-coil leak and servicing error tests, the leakage rate was higher in the A-coil test (using a constant flow rate) compared to the natural pressure decay used in the servicing error test.

Without mitigation, the flaming was of longer duration in the hallway even though the refrigerant release charge was smaller. Figure 138 shows the maximum temperatures at the ceiling level and near the floor. The highest temperatures occurred between 4 and 12 inches above the floor.

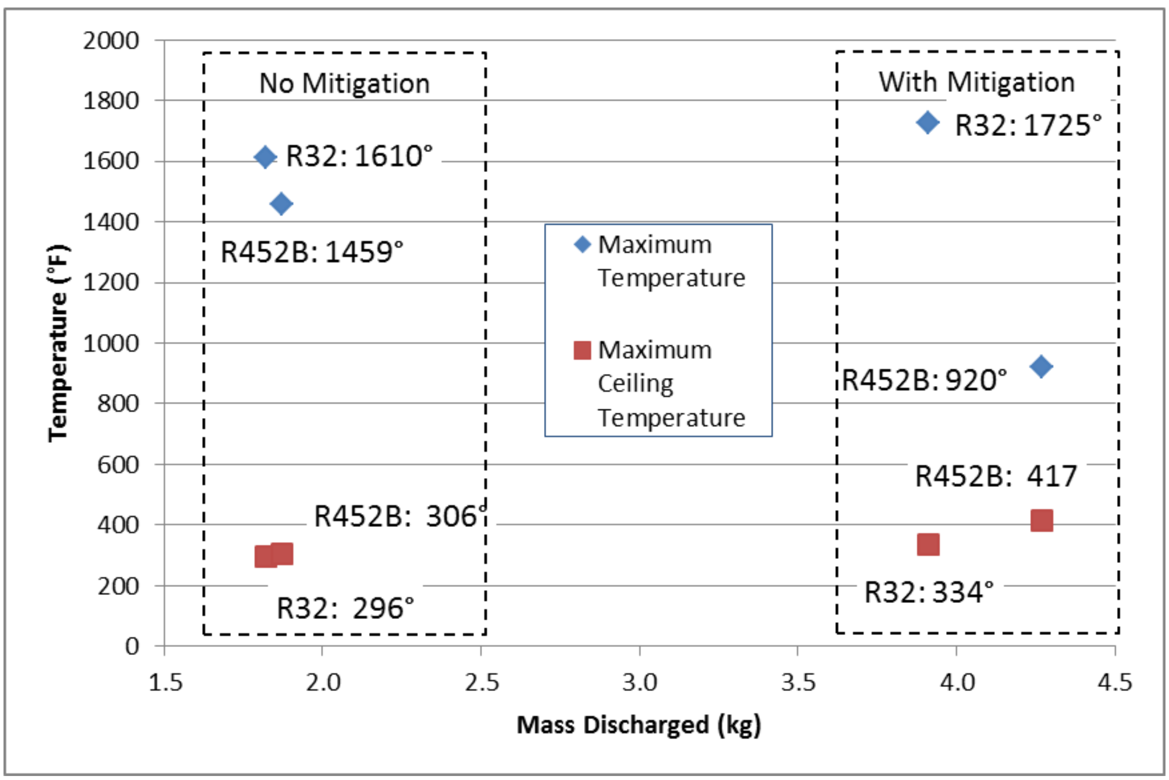


Figure 138 - Peak temperatures near floor and at ceiling

It was observed that some of the tea candles were extinguished by force of the air circulation once the mitigation action was initiated.

4.6.1.3.2. Discussion of Results – Servicing Line Error

Ignition was not observed with R-410A refrigerant. However, ignition occurred for both R-32 and R-452B refrigerants near the release location. There was no ignition of the refrigerant outside the utility closet.

The candle ignition sources were placed near the point of release. Once the discharge started, these candles were immediately extinguished by the discharge. Ignition was observed once the electric arc was energized. The location of the electric arc and the speed of the discharge combined to limit the ignited volume to the immediate vicinity of the electric arc. Additional testing would be needed to determine whether a larger flame could be initiated in a zone where concentrations are between the LFL and UFL.

4.6.1.4. Results – Leakage in A-Coil Scenario

A summary of test results are presented in Table 41. The table also shows the average pressure differential maintained between return and supply ducts during mitigation.

Table 41 – Residential A/C Leakage in A-Coil Test Summary

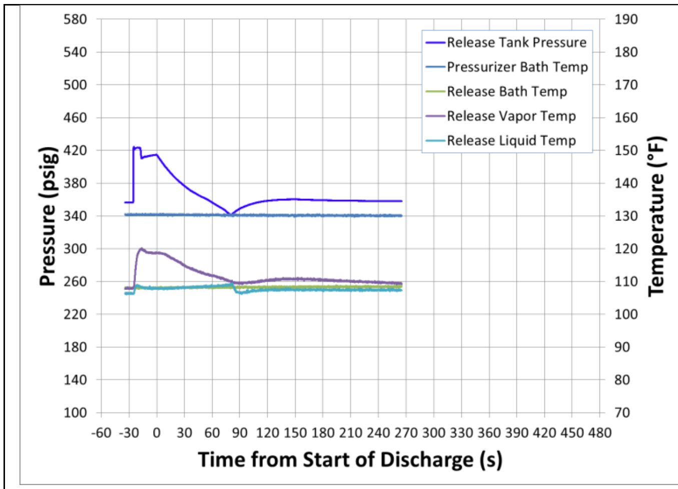
Test ID	Refrigerant	Total Mass Released (kg)	Ignition Result	Duration of flaming in Hallway (s)	Max. Temperature and Location (°F) /Location	Max Ceiling Temp (°F)	Average Pressure Diff. (Return and Supply) (mm Hg)	Std. Dev. (mm Hg)
Res02	R-32	3.91	Ignition	23	1725 / B12	334	0.218	0.052
Res03	R-452B	4.27	Ignition	23	920 / B04	417	0.216	0.048
Res04	R-32	1.82	Ignition	72	1610 / B08	296	Fan off	NA
Res05	R-452B	1.87	Ignition	64	1459 / B12	306	Fan off	NA

4.6.1.4.1. Res02

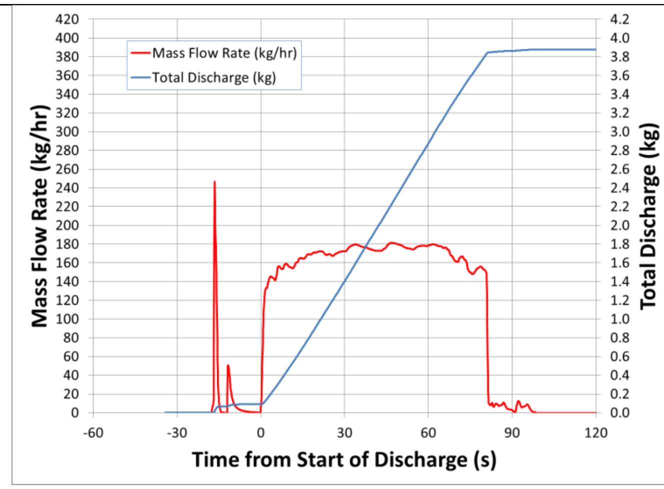
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Measured Release Quantity (kg)	Mitigation Method	Ignition Result
R-32	50	3.91	HVAC blower started 30s after refrigerant release is initiated.	Ignition

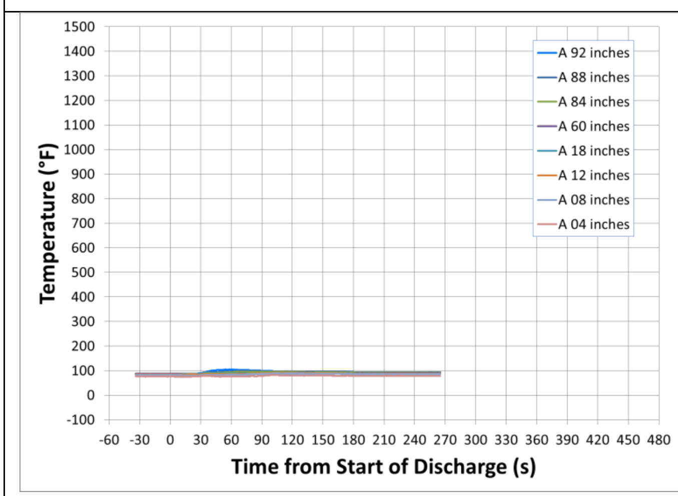
Liquid refrigerant was seen pooling near the return air grill in proximity of the HVAC unit, and ignition occurred 12s after refrigerant release was initiated. The flames were drawn into the return air grill after the HVAC return air blower was started. The flaming continued for approximately 23s and spread on the floor in the corridor towards the right wall. The test results are presented in Figure 139.



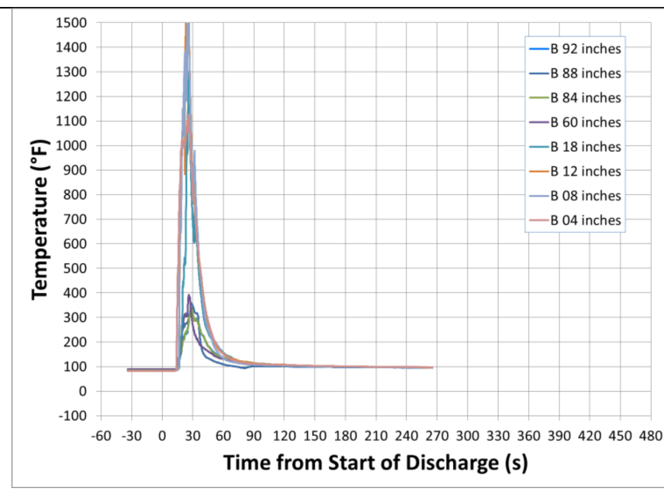
Pressure and Temperature in Pressurizer and Release Tanks



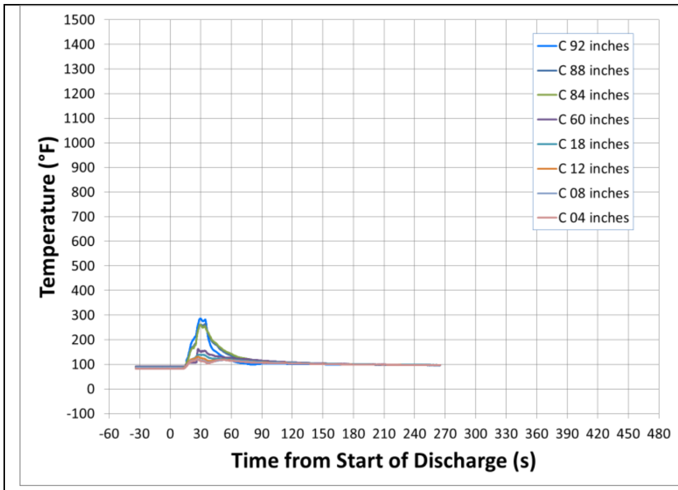
Refrigerant Release Rate



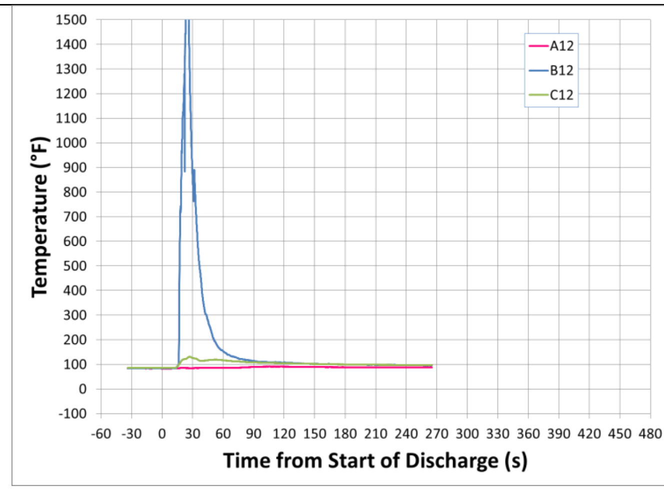
Temperature at Location A



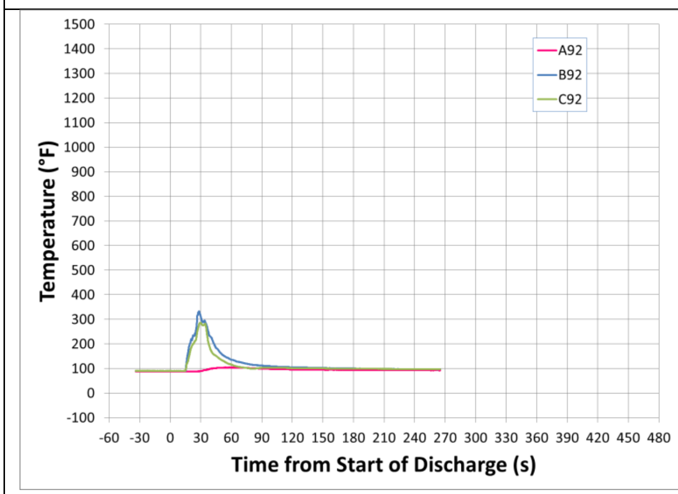
Temperature at Location B



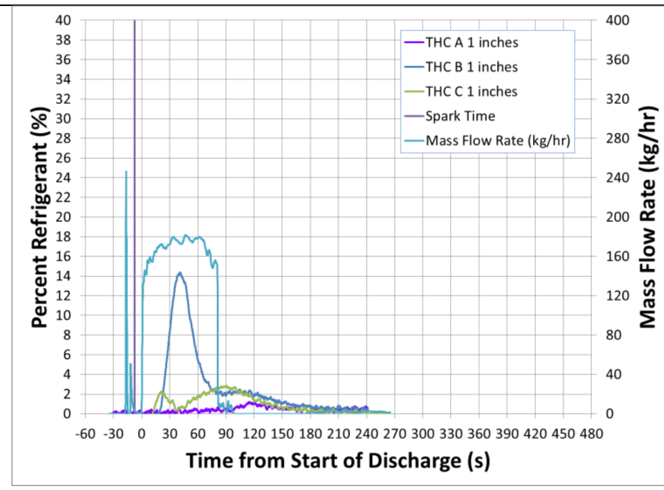
Temperature at Location C



Highest temperature: Temperature 12 in. height above the floor at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

Ignition of the refrigerant 12s after refrigerant release.

Flames 20s after refrigerant release.

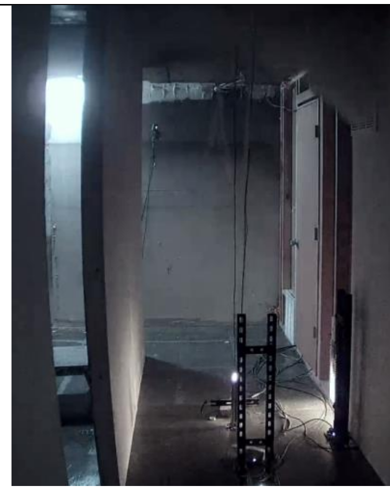
 28s after refrigerant release; flame spread over the floor in the hallway towards the right wall.	 34s after refrigerant release flaming in hallway ceased; and flaming observed in the HVAC unit with smoke emitting from supply grill.

Figure 139 – Test Results for Residential A/C Test Res02

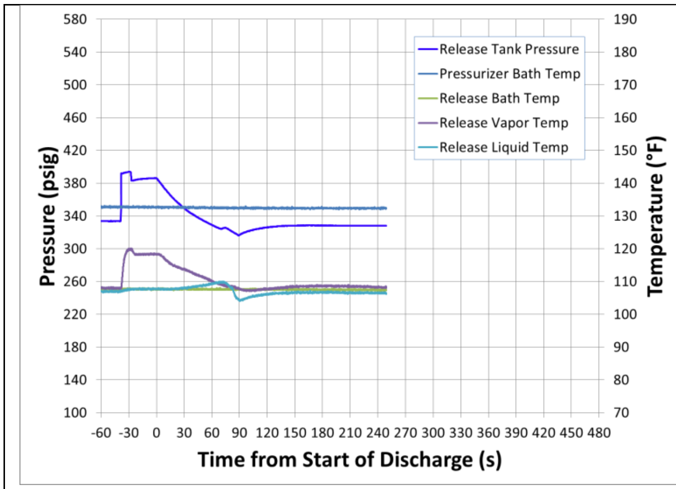
The flaming spread over the floor in the hallway towards the right wall. The highest temperature was recorded at Location B (outside the return grill), and 12 inches above the floor.

4.6.1.4.2. Res03

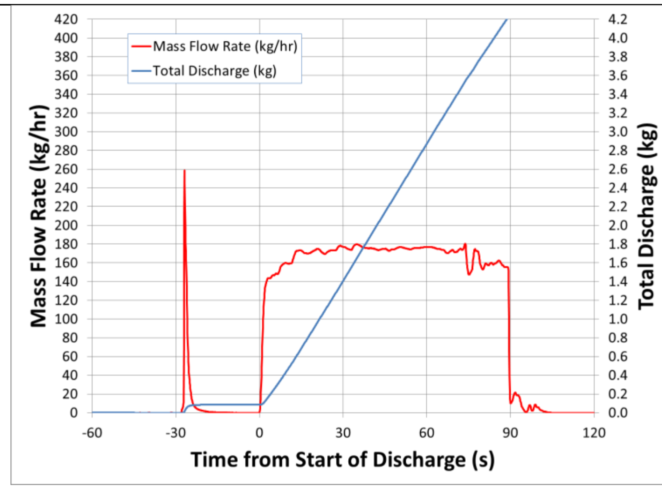
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Measured Release Quantity (kg)	Mitigation Method	Ignition Result
R-452B	50	4.27	HVAC blower started 30s after refrigerant release is initiated.	Ignition

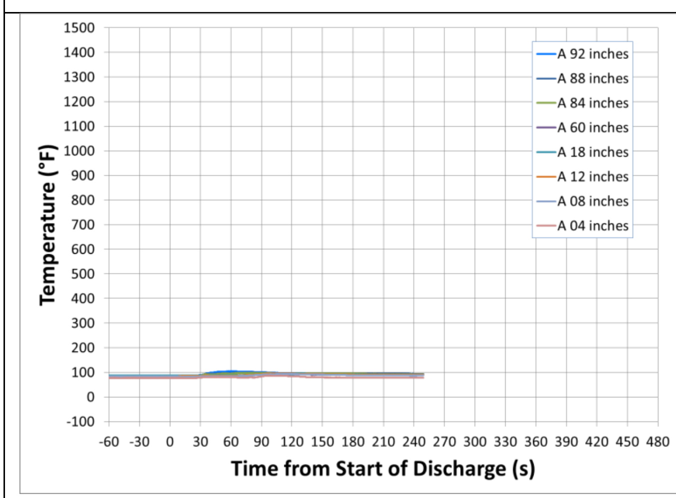
Ignition occurred 12s after refrigerant release was initiated. The flames were drawn into the return air grill after the HVAC return air blower was started. The flaming continued for approximately 23s after and spread on the floor in the corridor towards the nearest wall. The test results are presented in Figure 140.



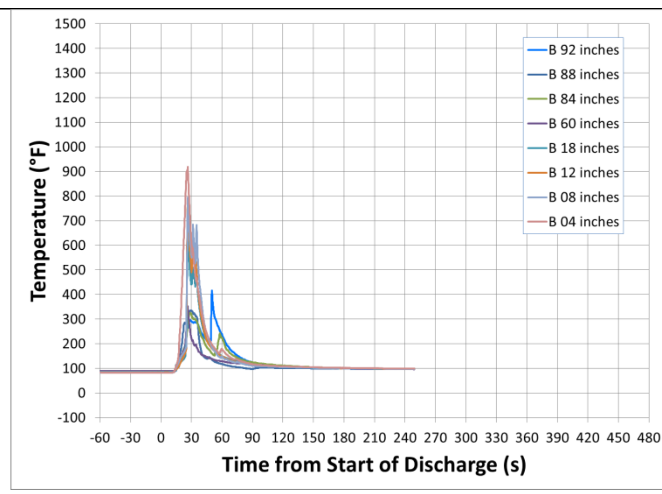
Pressure and Temperature in Pressurizer and Release Tanks



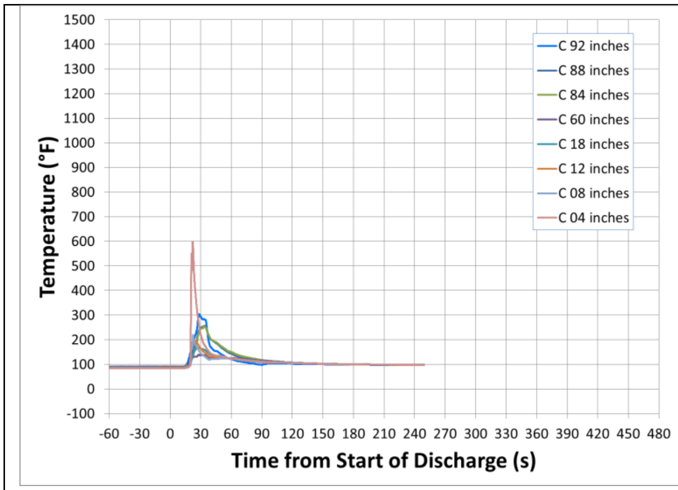
Refrigerant Release Rate



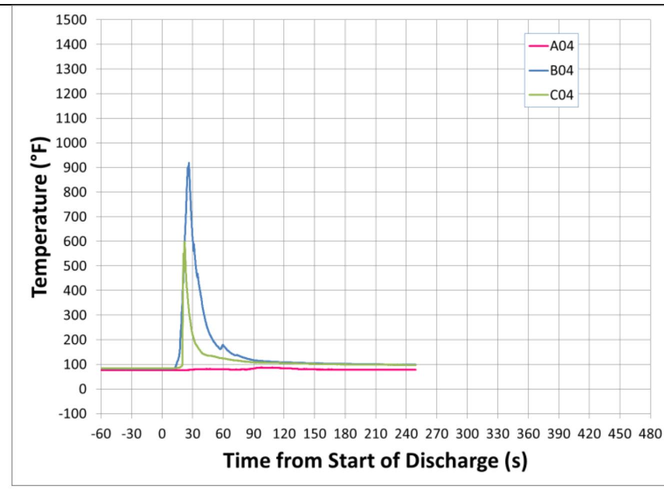
Temperature at Location A



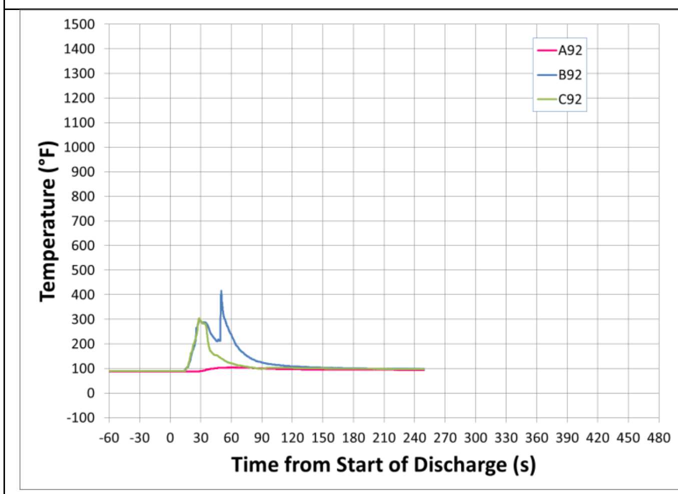
Temperature at Location B



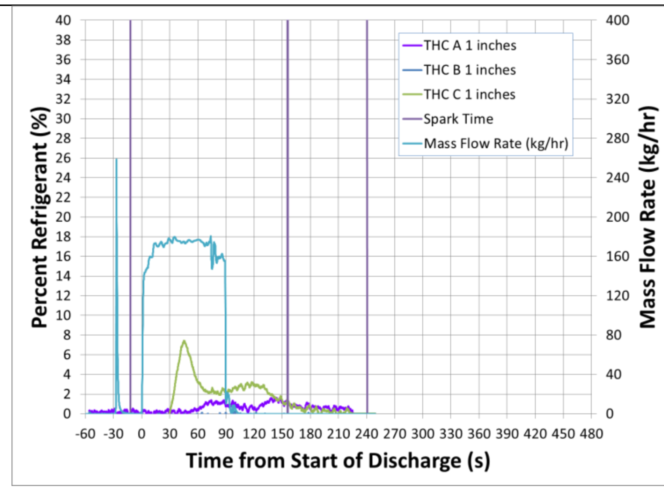
Temperature at Location C



Highest temperature: Temperature 4 in. height above the floor



Temperature at 92 in. height above the floor



Refrigerant Concentration

Ignition of the refrigerant 12s after refrigerant release.

Flames 20s after refrigerant release.

	
29s after refrigerant release; flame spread observed on the floor in the hallway twoard the right wall.	36s after refrigerant release; flaming in the HVAC unit and smoke emitting from supply grill.

Figure 140 - Test Results for Residential A/C Res03

The highest temperature was recorded at Location B, and 4 inches above the floor.

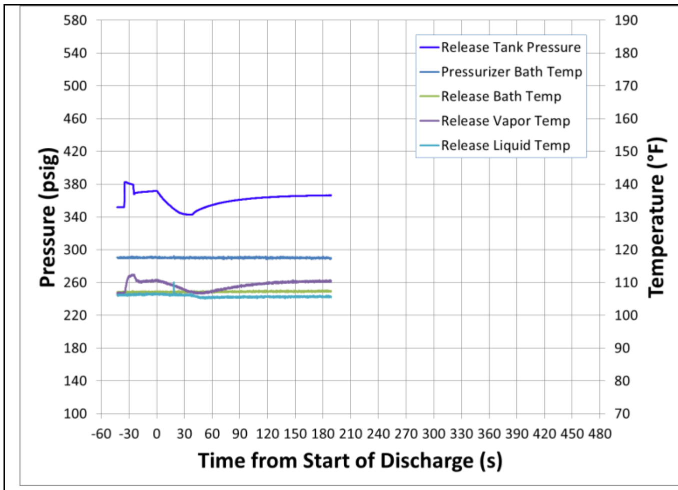
Since the ignition of the refrigerants for both R-32 and R-452B occurred before 15s, tests with starting the HVAC blower 15s after refrigerant release initiation were not conducted.

4.6.1.4.3. Res04

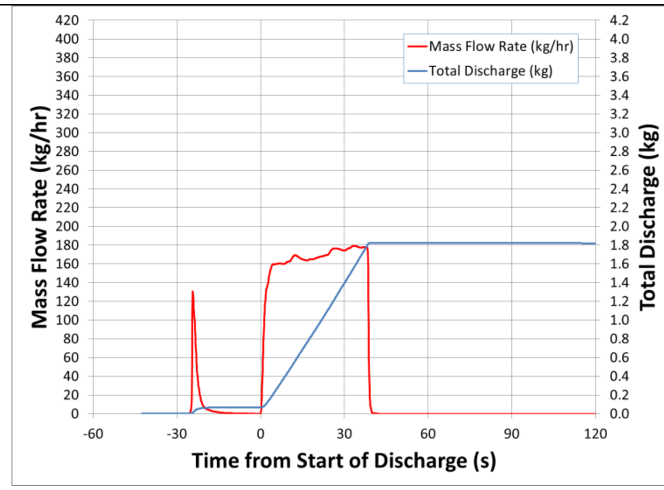
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Measured Release Quantity (kg)	Mitigation Method	Ignition Result
R-32	50	1.82	No mitigation	Ignition

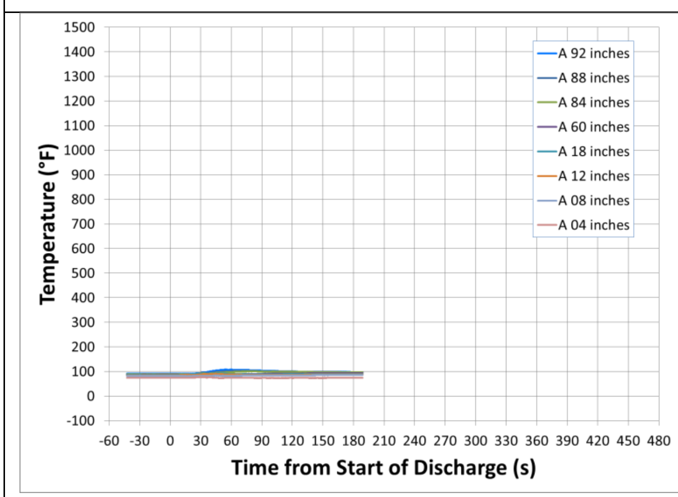
Ignition occurred 12s after refrigerant release was initiated. The flaming continued for approximately 72s. The flames spread along the hallway and also towards the return grill. The test results are presented in Figure 141.



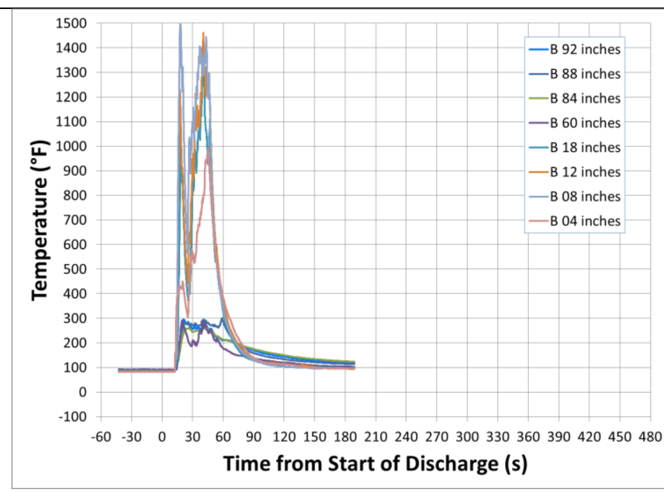
Pressure and Temperature in Pressurizer and Release Tanks



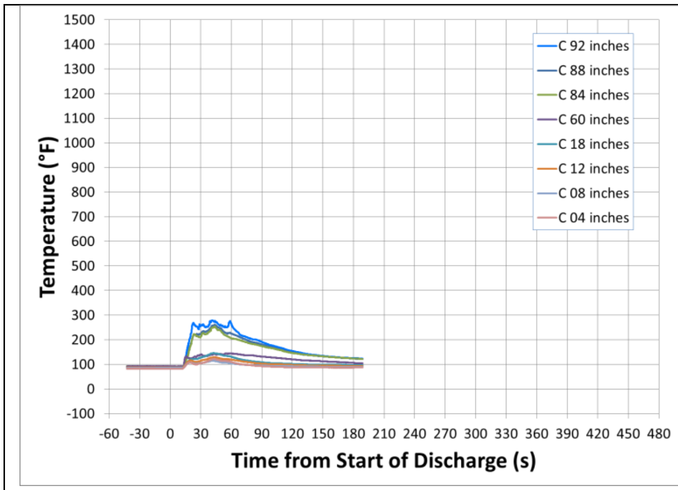
Refrigerant Release Rate



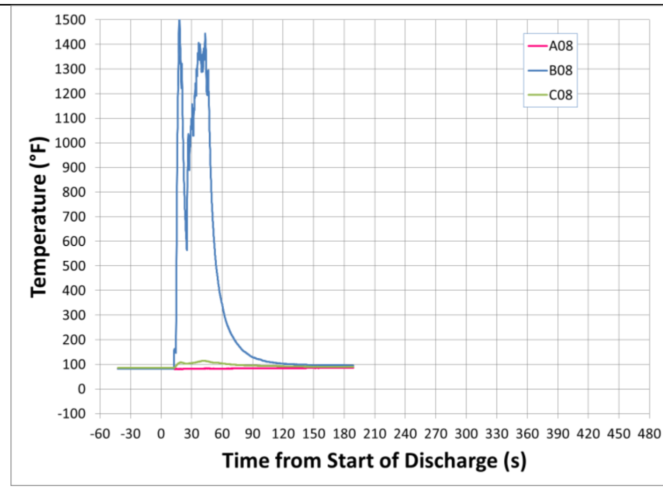
Temperature at Location A



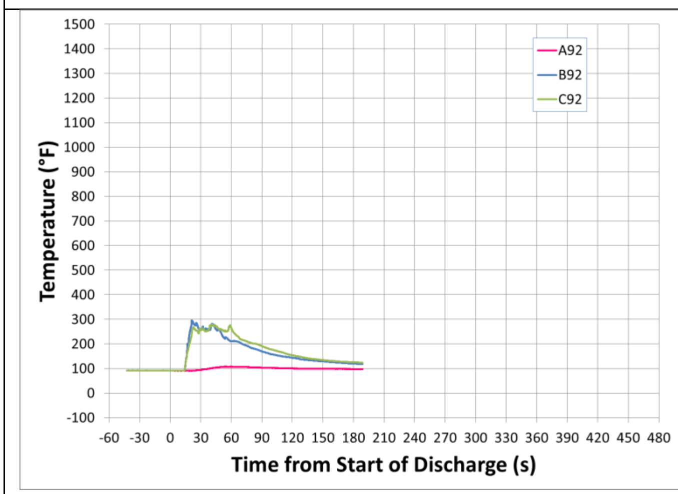
Temperature at Location B



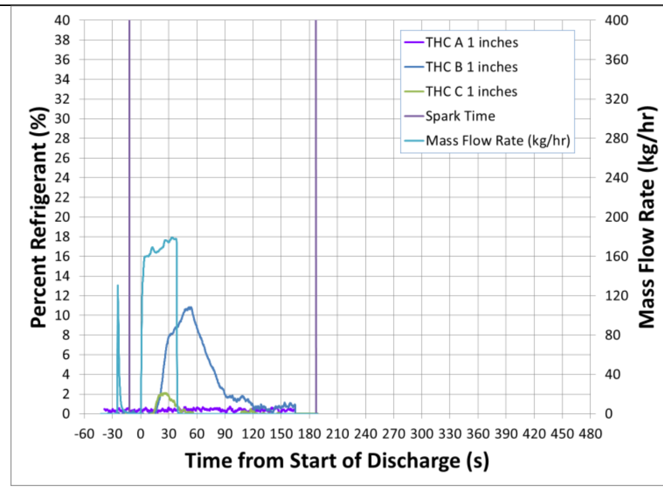
Temperature at Location C



Highest temperature: Temperature 8 in. height above the floor at Location B

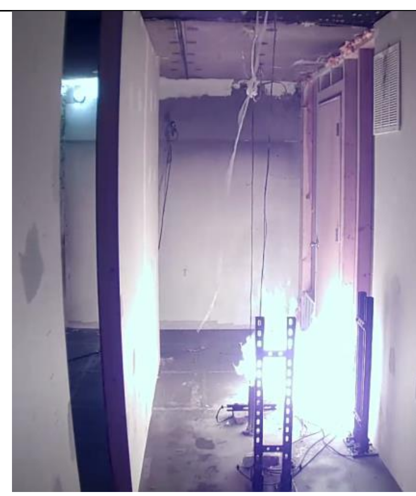


Temperature at 92 in. height above the floor



Refrigerant Concentration

Ignition of the refrigerant 12s after refrigerant release.



Flames 20s after refrigerant release; flames moves toward the return air grill.

	
16s after refrigerant release; flame spread observed on the floor in the hallway toward the right wall.	76s after refrigerant release; cheese cloth ignition all the way to the ceiling; all flaming ceased 84s after refrigerant release.

Figure 141 - Test Results for Residential A/C Res04

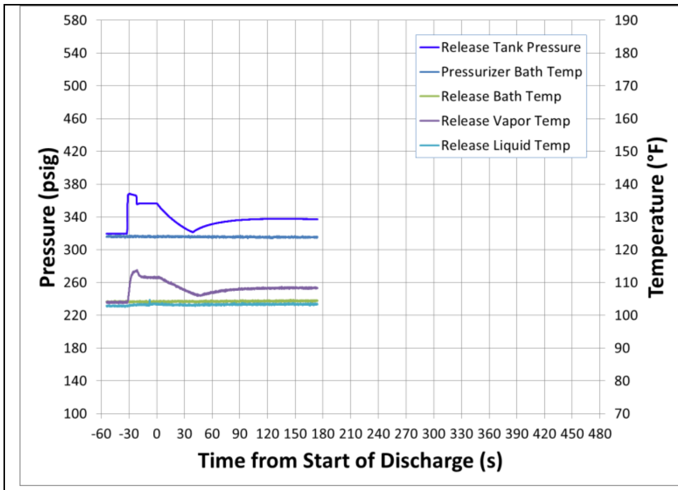
The highest temperature was recorded at Location B, and 8 inches above the floor.

4.6.1.4.4. Res05

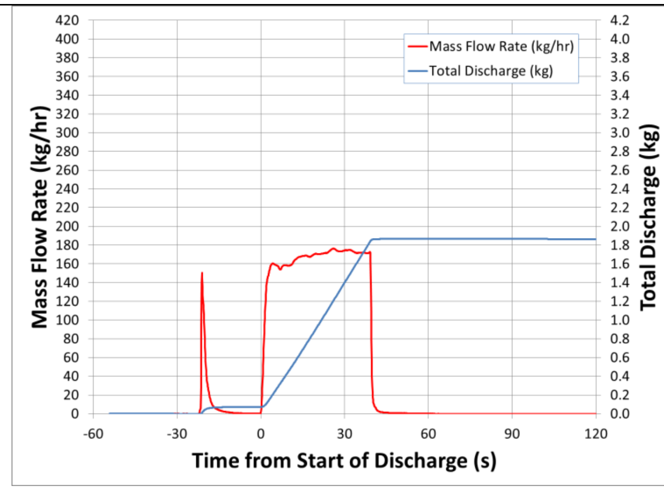
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Measured Release Quantity (kg)	Mitigation Method	Ignition Result
R-452B	50	1.87	No mitigation	Ignition

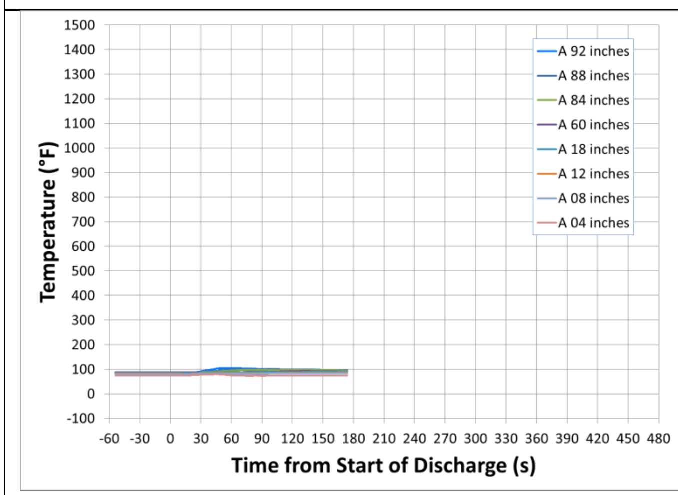
Ignition occurred 12s after refrigerant release was initiated. The flaming continued for approximately 62s. The flames spread along the hallway and also towards the return grill. The test results are presented in Figure 142.



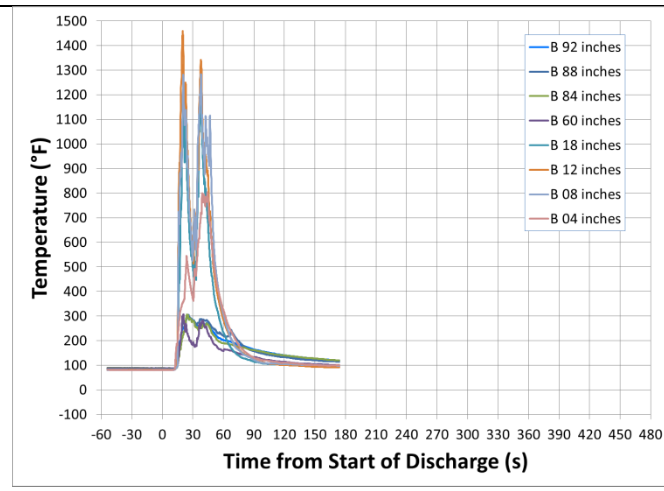
Pressure and Temperature in Pressurizer and Release Tanks



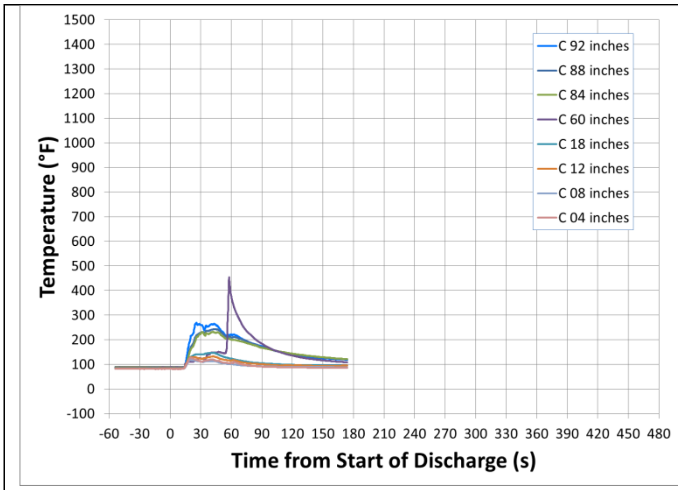
Refrigerant Release Rate



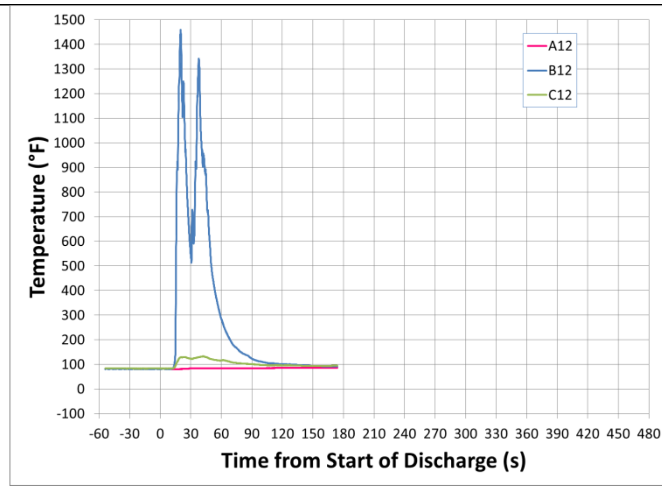
Temperature at Location A



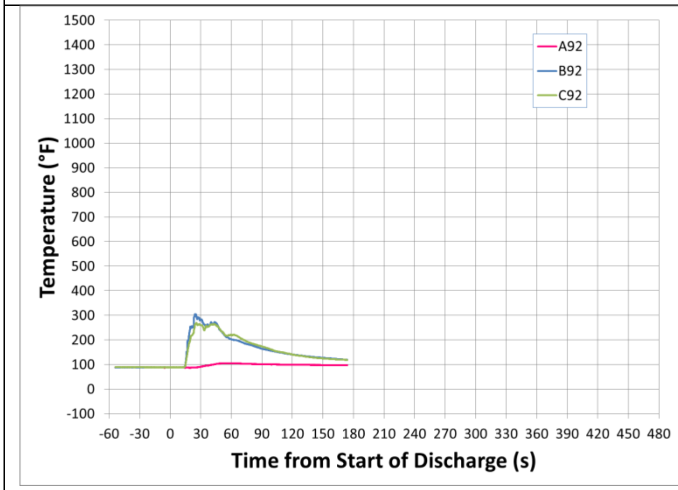
Temperature at Location B



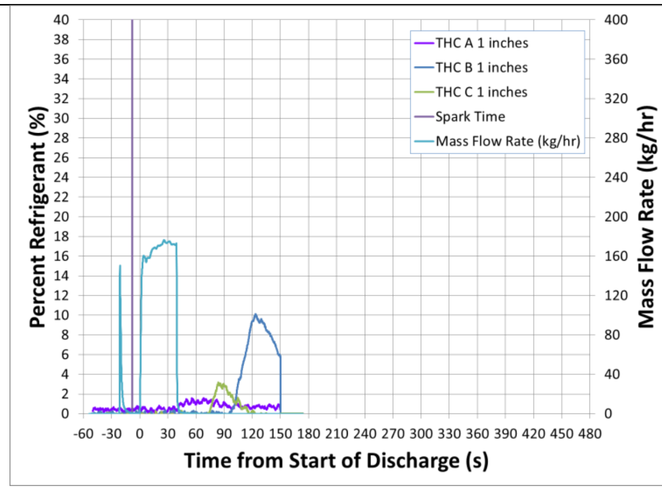
Temperature at Location C



Highest temperature: Temperature 12 in. height above the floor at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

Ignition of the refrigerant 12s after refrigerant release.

Flames 18s after refrigerant release; flames moves toward the return air grill.

	
27s after refrigerant release; flame spread observed on the floor in the hallway toward the right wall.	60s after refrigerant release; cheese cloth ignition all the way to the ceiling; all flaming ceased 76s after refrigerant release.

Figure 142 - Test Results for Residential A/C Res05

The highest temperature was recorded at Location B, and 12 inches above the floor.

4.6.1.6. Results – Leakage in Service Line Error Scenario

There was no ignition with R-410A refrigerant. In tests with R-32 and R-452B refrigerants, the ignition and flame were localized at the electric arc in proximity of the leakage. There was no ignition of refrigerants outside the closet

A summary of test results are presented in Table 42.

Table 42 – Residential A/C Service Line Error Test Summary

Test ID	Refrigerant	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	Max. Temperature and Location (°F) /Location	Total Mass Released (kg)	Ignition Result
Res06	R-410A + 30g lubricating oil	93	92	93 / C92	1.81	No ignition
Res07	R-32 + 30g lubricating oil	91	90	92 / A84	1.57	Ignition
Res08	R-452B + 30g lubricating oil	[1]	[1]	[1]	[1]	Ignition

Note: [1] Data acquisition inadvertently stopped after test was initiated. It was decided to continue with the test to obtain visual results since there was no ignition of refrigerants outside the utility closet with R-32 (Res04).

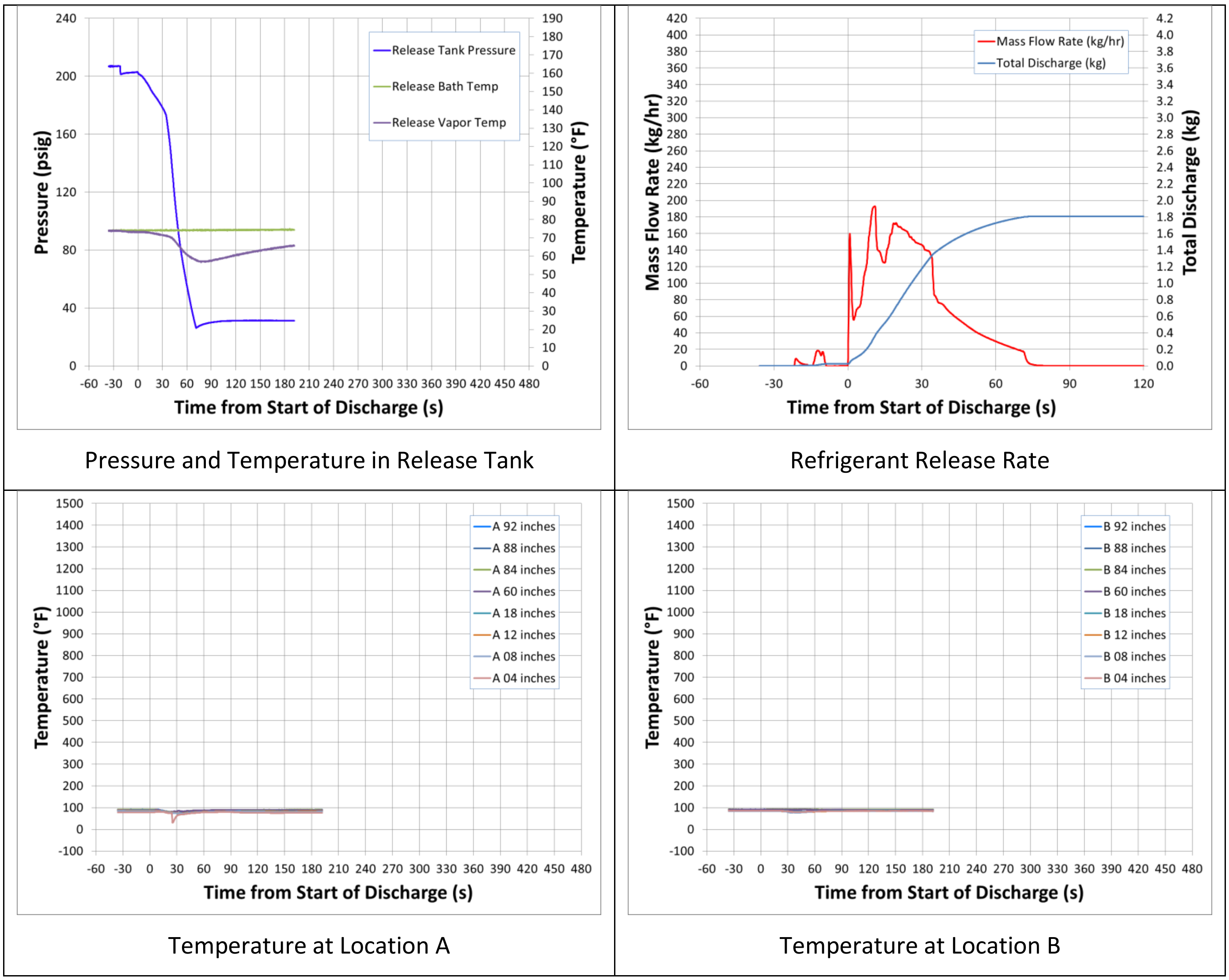
4.6.1.6.1. Res06

The test parameters for this test were as follows:

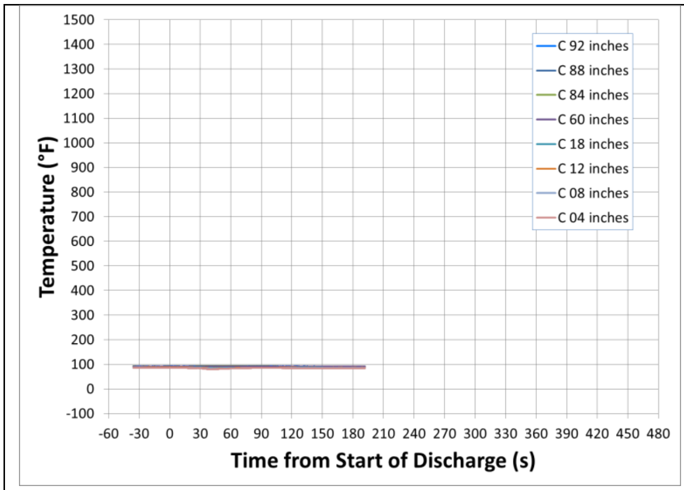
Refrigerant	Release rate (g/s)	Measured Release Quantity (kg)	Ignition Result
R-410A + 30g lubricating oil	66 g/s initial with natural pressure decay	1.81	No Ignition

The release of the refrigerant and lubricating oil mixture resulted in a fog in the room. Due to the velocity of discharge, the candle was blown out. During the test, there was no ignition observed in near the HVAC unit or at the other ignition sources (Locations, A, B, or C).

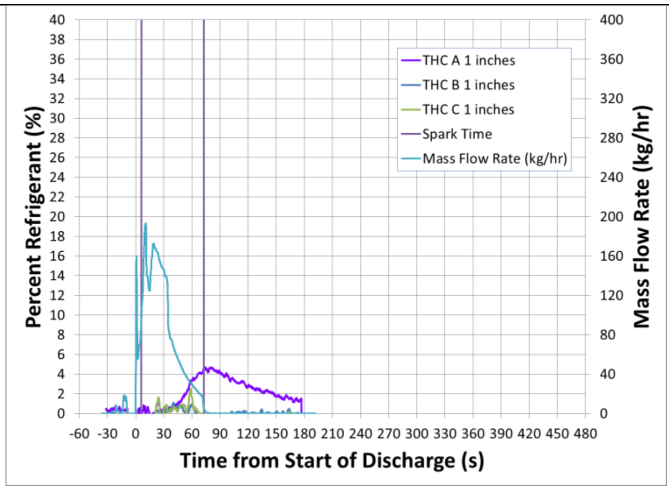
The results from the test are presented in Figure 143.



Pressure and Temperature in Release Tank	Refrigerant Release Rate
Temperature at Location A	Temperature at Location B



Temperature at Location C



Refrigerant Concentration

3s after initiation of refrigerant+oil release showing the ensuing jet

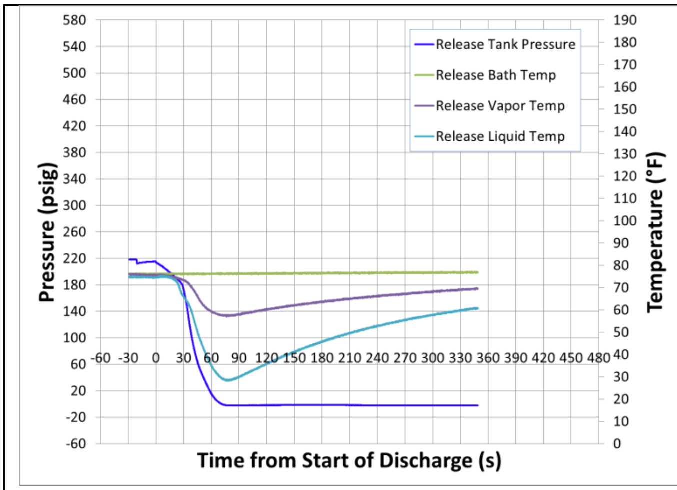
Figure 143 - Test Results for Residential A/C Res06

4.6.1.6.2. Res07

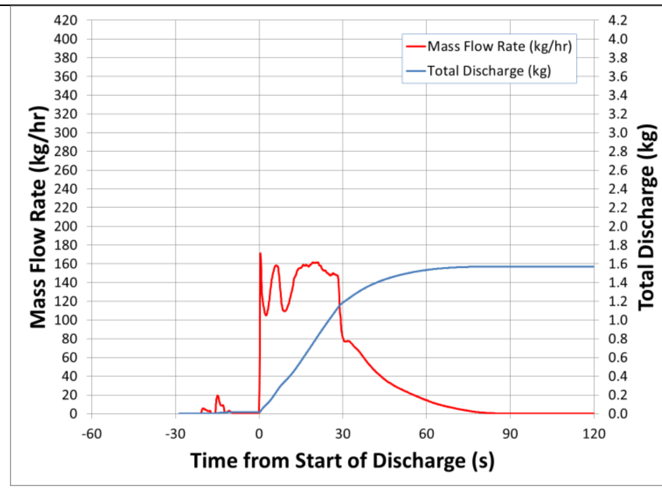
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Measured Release Quantity (kg)	Ignition Result
R-32 + 30g lubricating oil	66 g/s initial with natural pressure decay	1.81	Ignition

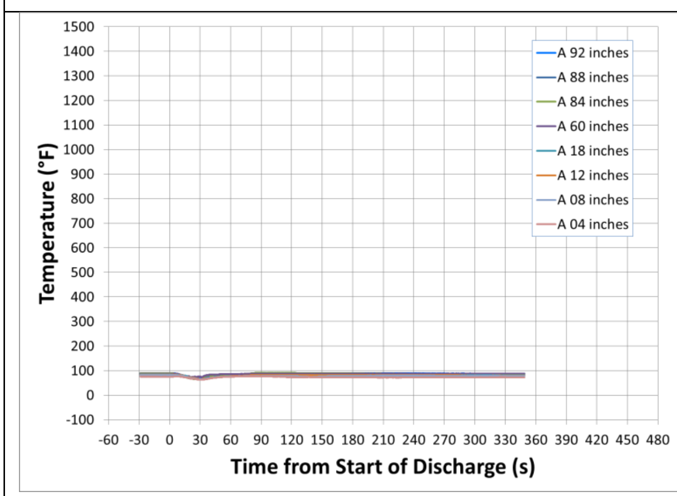
The release of the refrigerant and lubricating oil mixture resulted in a fog in the room. Due to the velocity of discharge, the candle was blown out. During the test, there was no ignition at locations A, B, or C outside the closet. However, the ignition of refrigerant was observed at the release location in the closet. The data are presented in Figure 144.



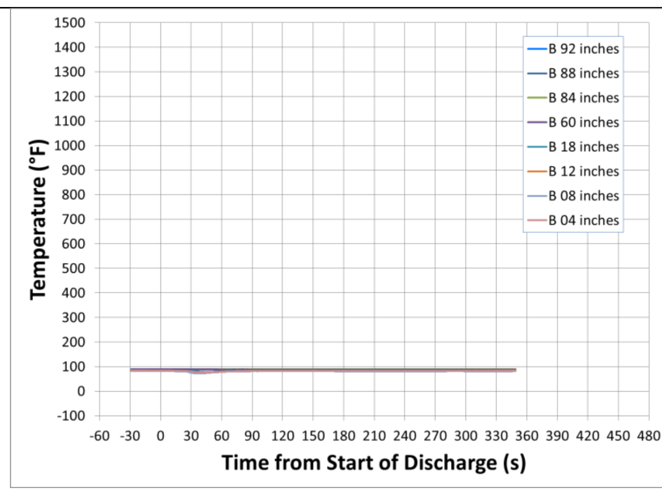
Pressure and Temperature in Release Tank



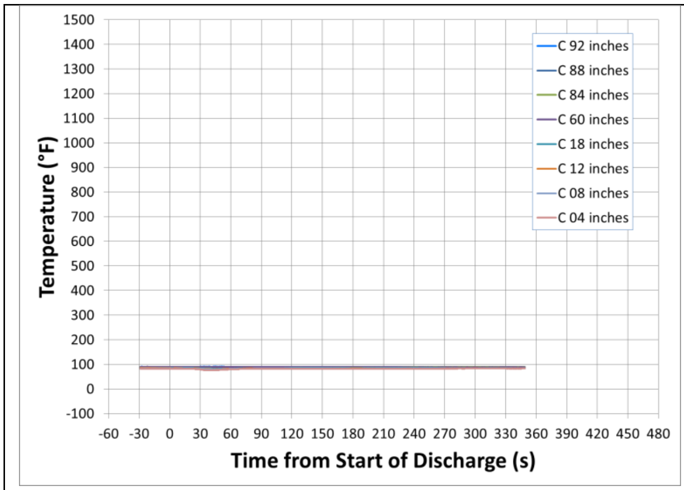
Refrigerant Release Rate



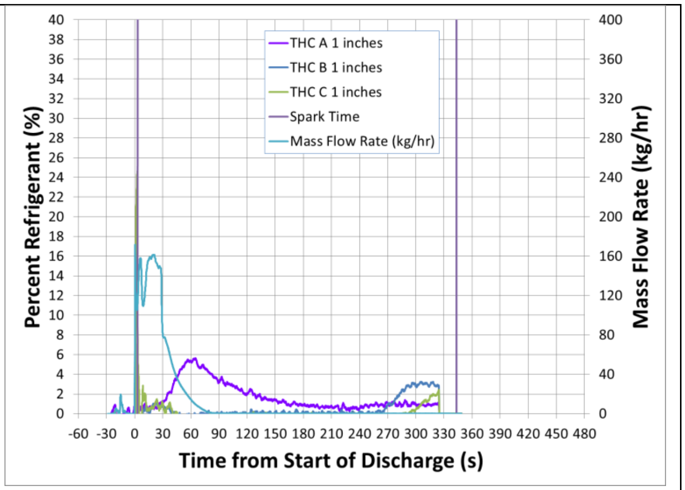
Temperature at Location A



Temperature at Location B



Temperature at Location C



Refrigerant Concentration

3s after initiation of refrigerant+oil release showing the ensuing jet

71s after initiation of refrigerant+oil release; flaming observed at release location.

Figure 144 - Test Results for Residential A/C Res07

4.6.1.6.3. *Res08*

The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Measured Release Quantity (kg)	Ignition Result
R452 + 30g lubricating oil	66 g/s initial with natural pressure decay	1.35	Ignition

The release of the refrigerant and lubricating oil mixture resulted in a fog in the room. Due to the velocity of discharge, the candle was blown out. During the test, there was no ignition at locations A, B, or C outside the closet. However, ignition was observed at the release location in the closet. Due to data acquisition equipment malfunction, most instrumentation data for this test are not available. The refrigerant release rate and total release are shown in Figure 145. The visual results from video recording are presented in Figure 146.

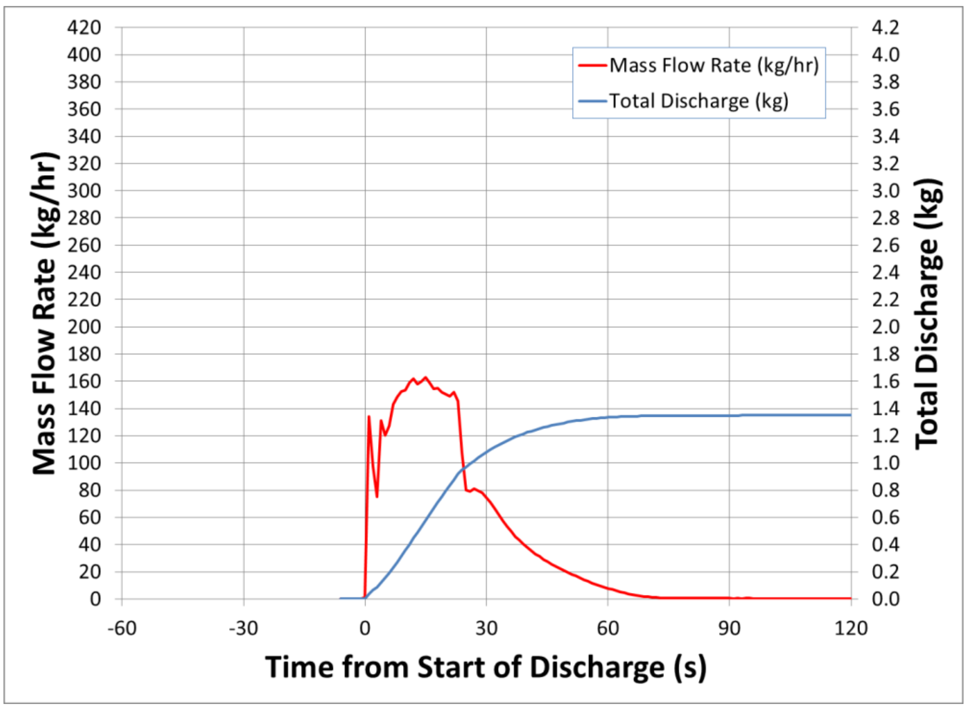


Figure 145 - Refrigerant Release Rate (RES08 test)

	
3s after initiation of refrigerant+oil release showing the ensuing jet	67s after initiation of refrigerant+oil release; flaming observed at release location.

Figure 146 - Test Results for Residential A/C Res08

4.6.2. Hermetic Electrical Pass-Through Terminal Failure Tests

The electrical terminal failure scenario involved the use of the outdoor section of a residential compressor/condenser unit. The test setup is shown in Figure 147, Figure 148, Figure 149, and Figure 150. The unit was placed in an open lab space without environmental conditioning.

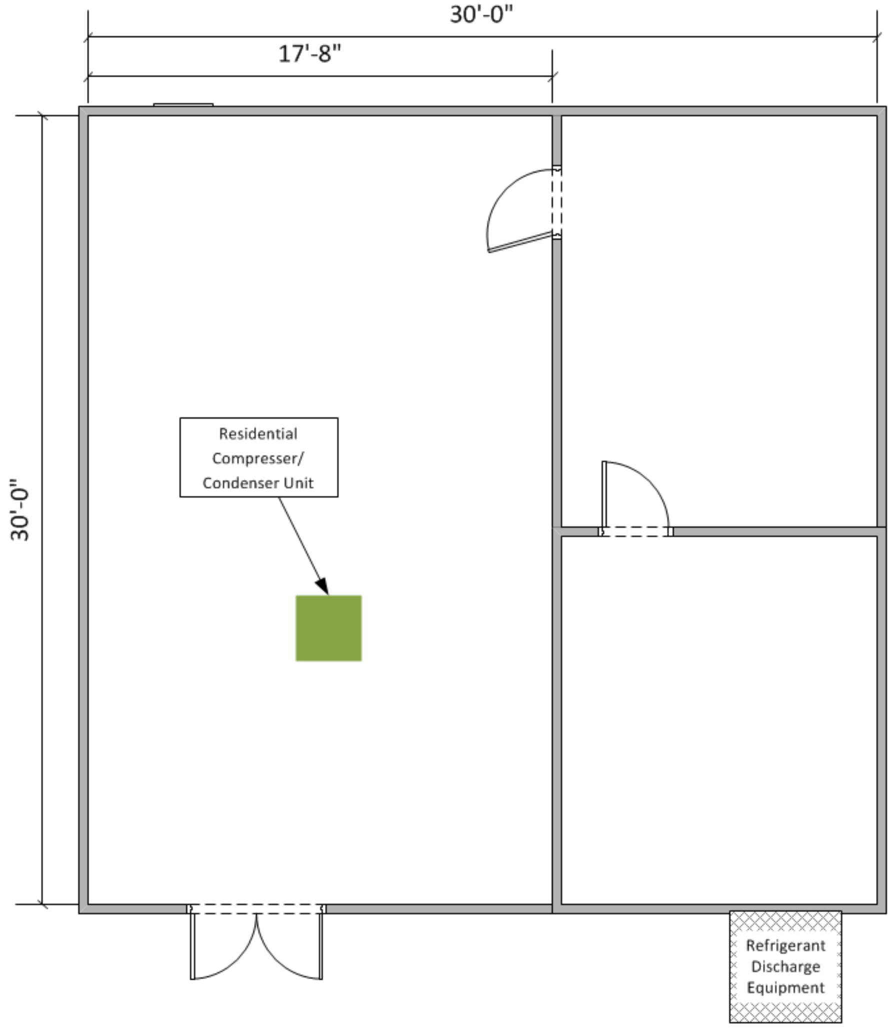


Figure 147 – Hermetic Electrical Pass-Through Terminal Failure Test Setup

Figure 148 – Exterior View of Condensing Unit

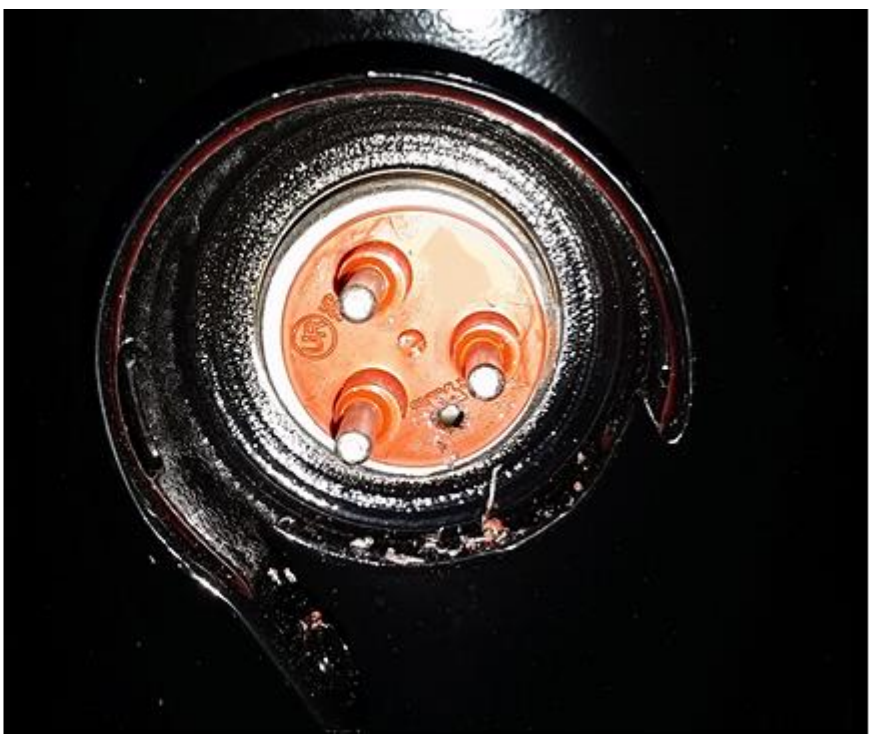


Figure 149 – Location of the intentional hole drilled in the body of the Hermetic Electrical Pass-Through Terminal

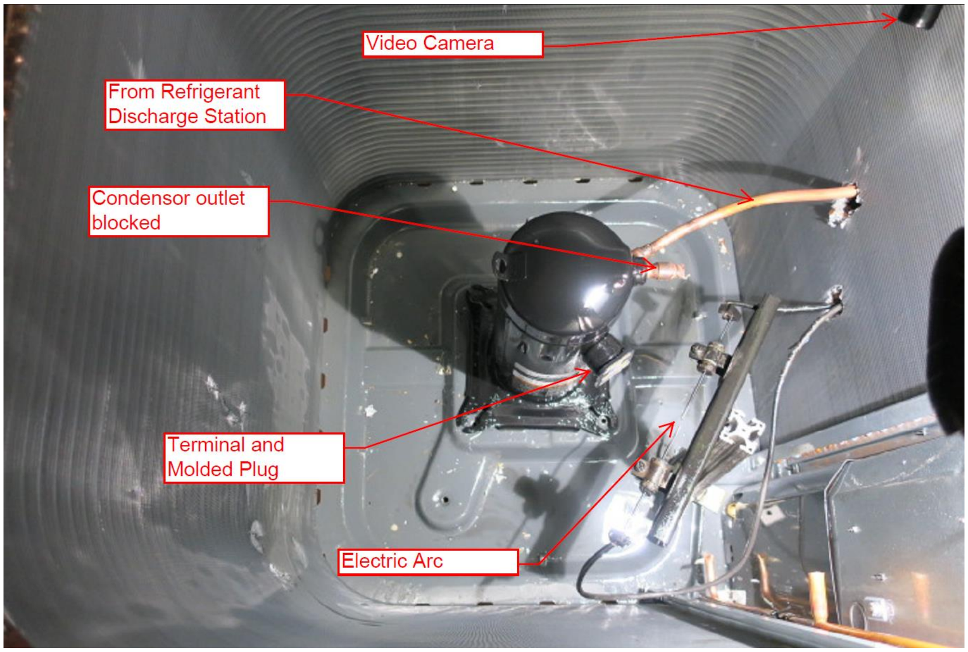


Figure 150 – Interior Arrangement of Condensing Unit Components

The instrumentation for this test was limited to the refrigerant discharge equipment and video.

4.6.2.1. Refrigerant Release

The leak was produced by drilling one (1) hole in the metal electrical terminal housing adjacent to the terminal pins (Figure 149). The hole was located to prevent damage to the glass seals around the pins. The diameter of the drilled leak hole was the same diameter as one single terminal pin (1/8 inch diameter). Refrigerant was directed into the compressor through the suction fitting via a 1/2 inch diameter tube. The length of the tube was approximately 6 meters and was attached to a 1 by ½ inch reducer at the exit of the mass flow control valve. The discharge port was fitted with a brazed cap to ensure that the refrigerant exited solely through the drilled hole in the terminal. Prior to each test, the refrigerant in the refrigerant release tank was adjusted to a temperature of 70°F. The flow controller was initially set to release 66 g/s (525 lb/hr), however the actual initial flow rate was a function of the pressure differential and the restrictions in the system. The initial flow rate was based on the expected mass flow rate through a typical A/C system. The total release amount is indicated in Table 43. This amount was derived from the nameplate for a heat pump unit with 85 ft. of lineset.

A test matrix of refrigerant release quantity is presented in Table 43.

Table 43 – Hermetic Electrical Pass-Through Terminal Failure Test Matrix

Refrigerant	Test Number	Planned Discharge (kg)
R-410A	Term01	5.25
R-452B	Term02	4.24
R-410A	Term03	5.25
R-32	Term04	3.85

Term03 with R-410A was a repeat of Term01 due to concern about seating the molded plug on the electrical terminals. With the exception of the first test, the molded plug was firmly seated on the electrical terminal before the compressor was installed in the unit housing.

A new compressor was used in each test to insure that a full charge of oil was available to be discharged during the test.

4.6.2.2. Test Procedure

The following procedure was used to initiate each test:

1. Confirm release refrigerant tank temperature of 70 ± 5°F.
2. Initiate data acquisition and video capture 30 seconds prior to discharging refrigerant.
3. Develop vacuum (less than 1mm Hg) between the release tank and flow meter.
4. Energize condenser fan and confirm operation based on the cheesecloth attached above the condenser unit.
5. Open the valve between release tank and the flow meter and hold for 5 seconds.
6. Energize the solenoid valves to enable refrigerant discharge.
7. Turn on electric arc ignition source.
8. Open the control valve to initiate refrigerant discharge through the mass flow meter.
9. At the completion of the discharge, de-energize the solenoid valves.
10. Continue to collect data until all flaming has ceased for at least 2 minutes.
11. Vent the test room.

After each test, the test facility was exhausted through UL's smoke abatement system, and the conditions in the facility were monitored with open path gas FT-IR. Staff re-entered the test facility only after the gas FT-IR indicated normal ambient conditions.

After the conclusion of each test the interior surfaces of the condensing unit were cleaned of any oil residue using an adsorbent paper towel. The compressor and molded plug were replaced with new samples. For test identified as Term01 the compressor was installed in the unit and secured in place and then the molded plug was installed. For the remaining tests, the molded plug was installed on the unit and then the compressor/plug assembly was secured to the condensing unit base pan.

During refrigerant discharge, oil became entrained in the refrigerant flow and exited out of the hole along with the refrigerant.

4.6.2.3. Summary of Findings – Hermetic Electrical Pass-Through Terminal Failure Tests

The results from the Hermetic Electrical Pass-Through Terminal failure tests showed that R-452B ignited under these test conditions. R-410A did not ignite. It was anticipated that R-32 would ignite under these same conditions, but an electrical interference caused reduction in the overall rate of R-32 discharge (additional information below). This slower rate of the R-32 discharge resulted in refrigerant/air mixtures that were not ignitable.

Additionally, it was observed that the molded plug was ejected from the terminal block in tests 1, 3, and 4. In test 2 with R-452B, the molded plug was unseated, but not ejected. This difference in ejection or non-ejection of the molded plug resulted in a different pattern of the refrigerant/oil mixture which contributed to the ignitability of the refrigerant/air mixture in the R-452B test.

Figure 151 compares the release tank pressures during the R-32 test (Test 4) and the R-452B test (Test 2). The stop/start nature of the R-32 release is visible in the chart. The data show R-32 pressure declining, and then increasing in pressure approximately every 30 seconds (20 seconds of decrease and 10 seconds of increase).

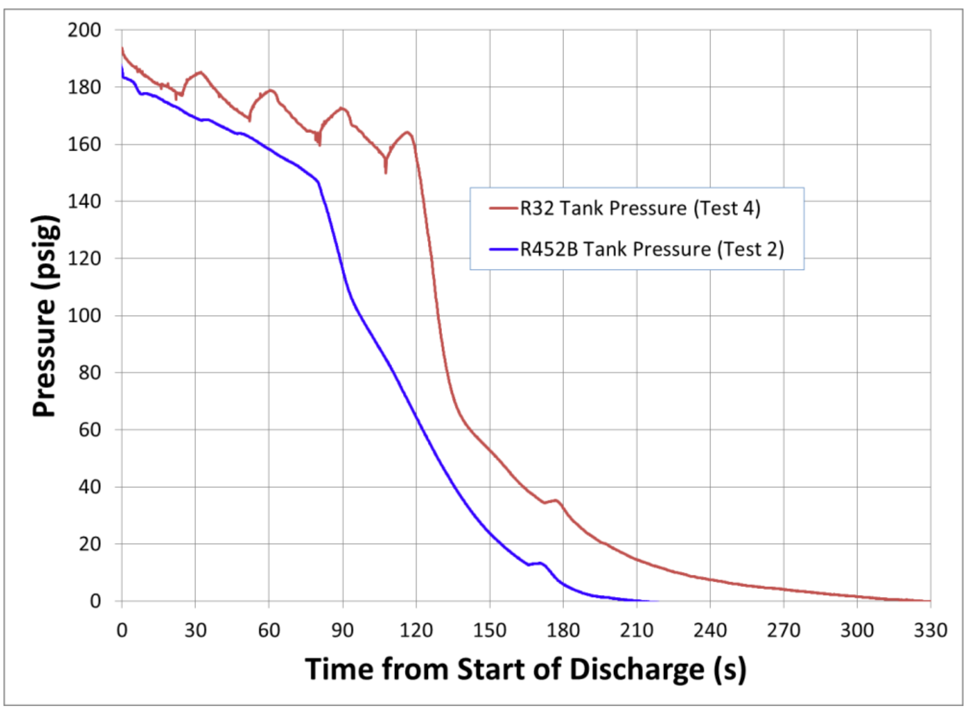


Figure 151 – Comparison of Release Tank Pressures during Hermetic Electrical Pass-Through Terminal Failure Tests

4.6.2.3.1. Oil Entrainment

All electrical terminal failure tests resulted in entrainment and discharge of the oil contained in the compressor (likely a normal scenario in a leak such as this). This was evidenced by the need to clean oil from surfaces inside and outside of the condenser enclosure after each test.

4.6.2.3.2. Electrical Interference

An examination of Figure 150 shows that the cables for the electric arc ignition source were threaded into the condenser enclosure which then split and routed to either end of the electric arc ignition source. This formed a current loop which had an effect of inducing voltages in the surrounding metal components. These induced voltages caused false readings of the refrigerant mass flow rate (test 3 and 4). In test 4 these voltages caused the air solenoid to chatter open and closed several times, when it was intended that the solenoid remain open throughout the test.

4.6.2.4. Results

A summary of test results are presented in Table 44.

Table 44 – Hermetic Electrical Pass-Through Terminal Scenario Summary

Refrigerant	Test Number	Planned Discharge (kg)	Measured Discharge (kg)	Result
R-410A	Term01	5.25	3.93	No Ignition
R-452B	Term02	4.24	3.38	Ignition
R-410A	Term03	5.25	6.00	No Ignition
R-32	Term04	3.85	3.28	No Ignition

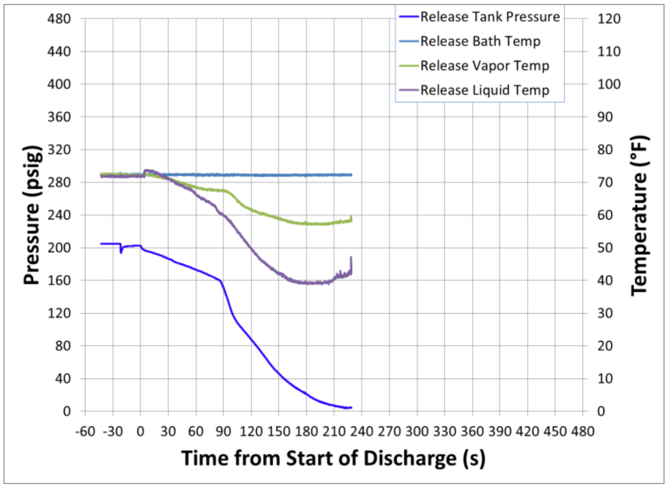
4.6.2.4.1. Term01:

The test parameters for this test were as follows:

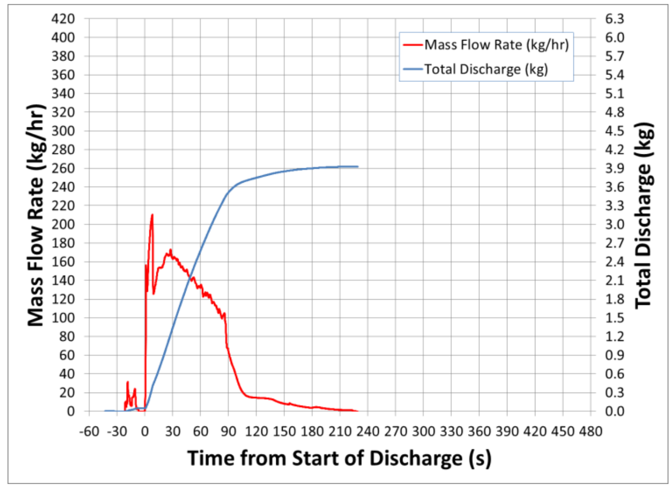
Refrigerant	Initial Release rate (g/s)	Planned Discharge (kg)	Ignition Result
R-410A	66	5.25	No ignition

There was no ignition during the test. The molded plug was ejected from the electrical terminal during the refrigerant release. The condenser fan remained operational during the entire test. After the test, the unit was inspected and there was evidence the oil from the sump of the compressor had been discharged through the hole in the electrical terminal. The oil had been deposited on the interior surfaces of the condenser as well as deposited on the grill fan blades of the condenser fan.

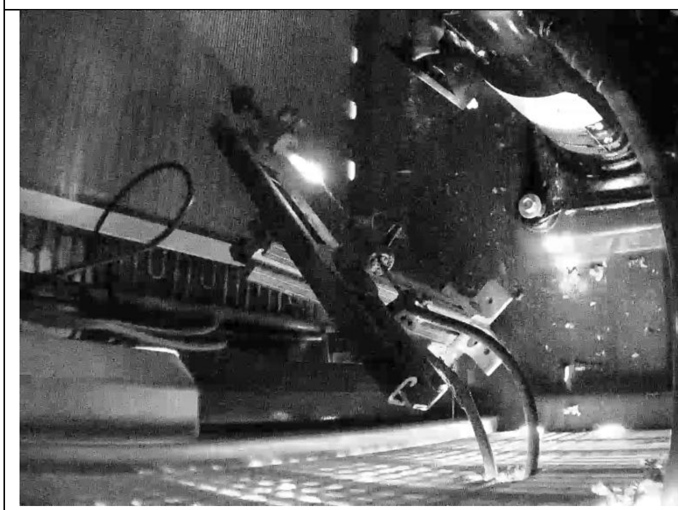
The test results are presented in Figure 152.



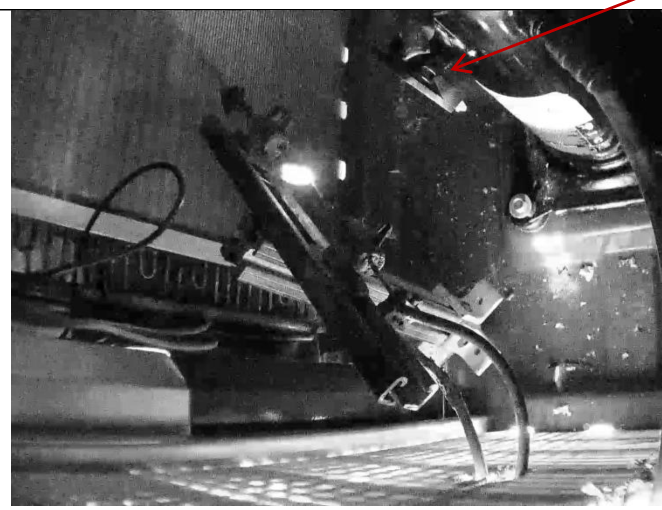
Pressure and Temperature in Release Tank



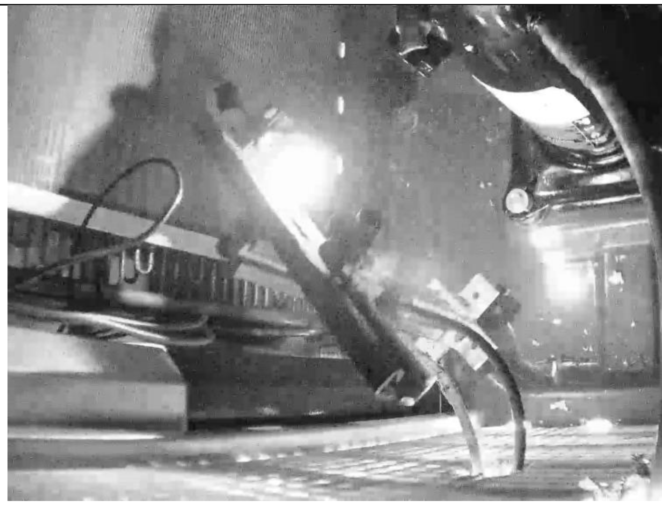
Refrigerant Release Rate



Initial Position of Molded Plug



Displacement of Molded Plug approximately 14s after release



Molded Plug no longer attached to compressor (16s after release)

Figure 152 – Data from Term01

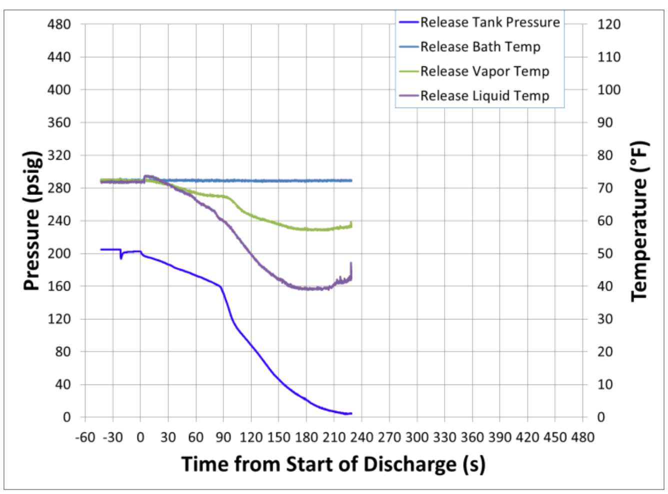
4.6.2.4.2. Term02:

The test parameters for this test were as follows:

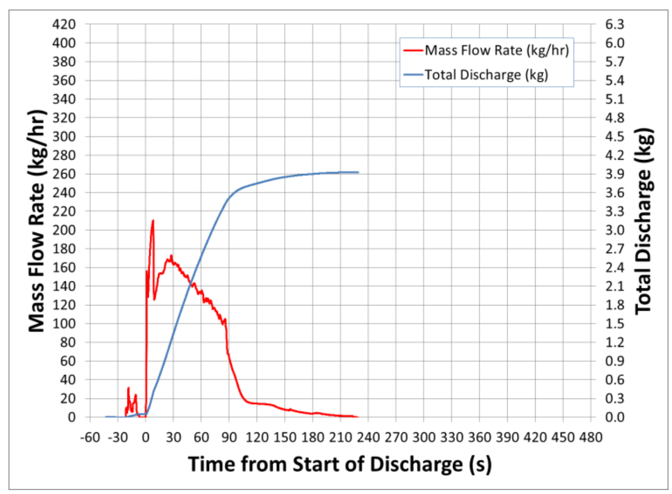
Refrigerant	Initial Release rate (g/s)	Planned Discharge (kg)	Ignition Result
R-452B	66	4.24	Ignition

The video showed that the refrigerant oil mixture ignited during a period from 55 to 102 seconds after the start of the release. However there was no sustained combustion and the flame remained generally contained within the condenser cabinet. There was no evidence of ignition of a strip of cheese cloth attached to the top of the condenser plate. The molded plug remained attached to the compressor during the refrigerant release; however it was displaced from its initial position. The condenser fan remained operational during the entire test. After the test, the unit was inspected and there was evidence that the oil from the sump of the compressor had been discharged through the hole in the electrical terminal. The oil had been deposited on the interior surfaces of the condenser as well as deposited on the grill fan blades of the condenser fan.

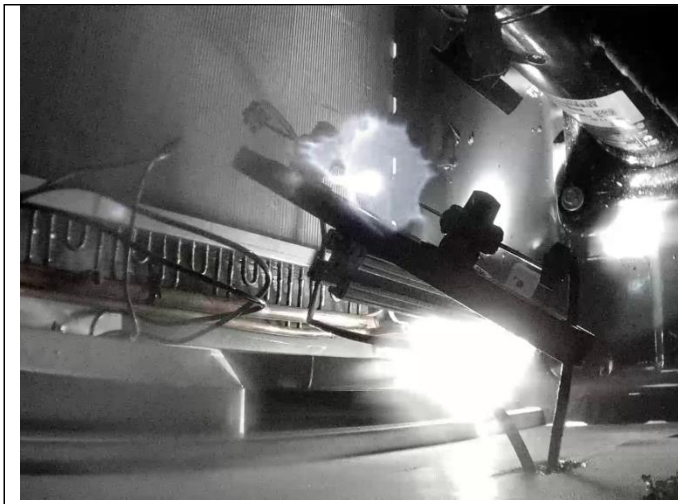
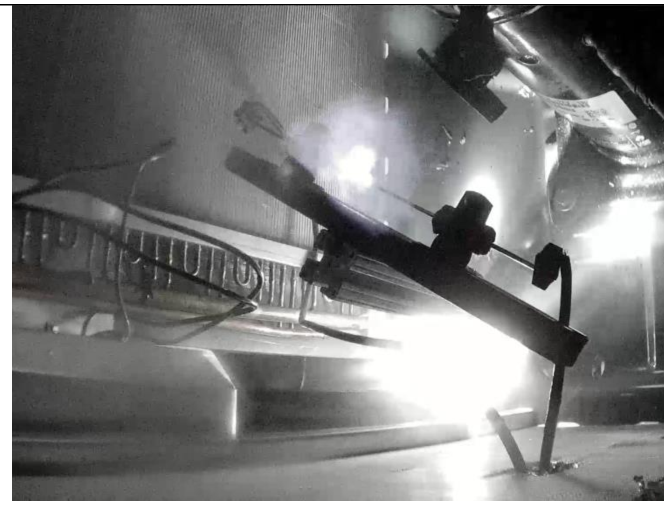
The test results are presented in Figure 153.



Pressure and Temperature in Release Tank



Refrigerant Release Rate

 Initial Position of Molded Plug	 Displacement of Molded Plug and Refrigerant Release (19s after release start)
 Video still showing ignition (55 s after release start)	 Video still showingignition (62 s after release start)
 Video still showing ignition (82 s after release start)	 Video still showing ignition (102 s after release start)

	
Side View of Molded Plug after Test	Top View of Molded Plug after Test

Figure 153 – Data from Term02

4.6.2.4.3. Term03:

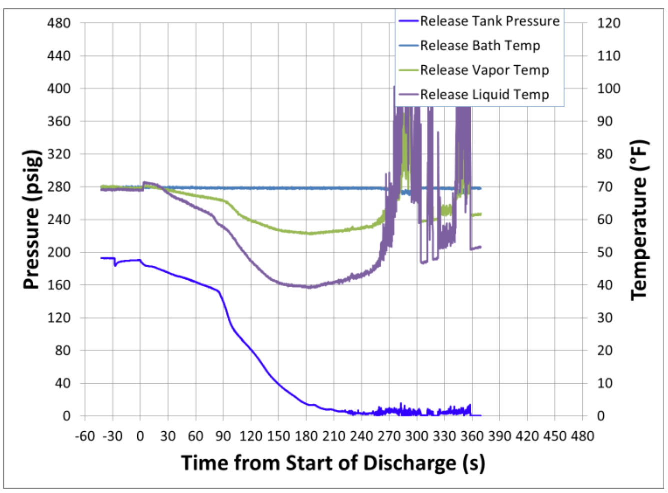
The test parameters for this test were as follows:

Refrigerant	Initial Release rate (g/s)	Planned Discharge (kg)	Ignition Result
R-410A	66	5.25	No ignition

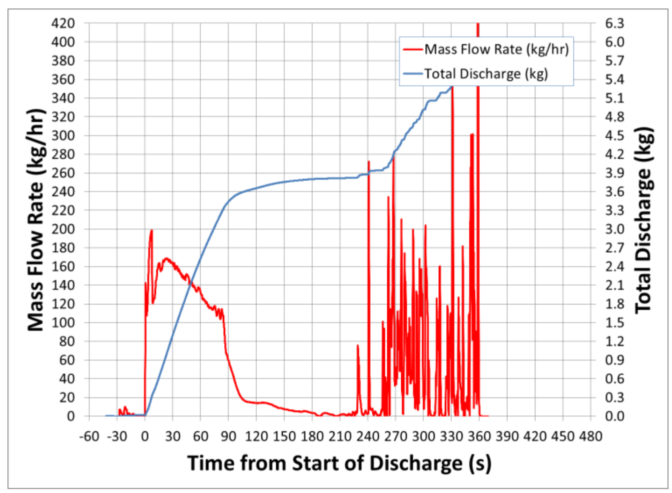
There was no ignition during the test. The molded plug was ejected from the electrical terminal during the refrigerant release. The condenser fan remained operational during the entire test. After the test, the unit was inspected and there was evidence that the oil from the sump of the compressor had been discharged through the hole in the electrical terminal. The oil had been deposited on the interior surfaces of the condenser as well as deposited on the grill fan blades of the condenser fan.

Electrical interference from the electric arc ignition source caused the mass flow meter to report a false signal at 240 seconds after the release began. The actual release amount is estimated to be between 3.9 and 4.2 kg when the pressure in the release tank had dropped to near atmospheric pressure.

The test results are presented in Figure 154.



Pressure and Temperature in Release Tank



Refrigerant Release Rate

Noise in Mass Flow Rate was due to interferiance caused by the high voltage ingition source.

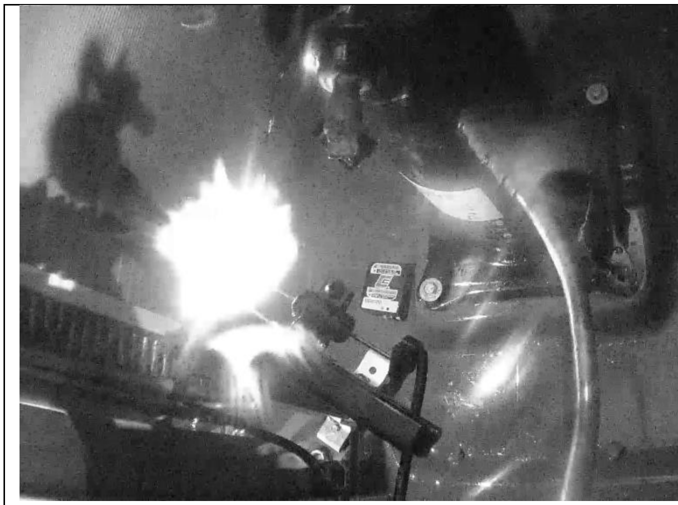
 Molded Plug no longer attached to compressor (20s after release)	 Discharge of Refrigerant (42s after release)
 Evidence of oil being depoisited on interior surfaces and basepan.	

Figure 154 – Data from Term03

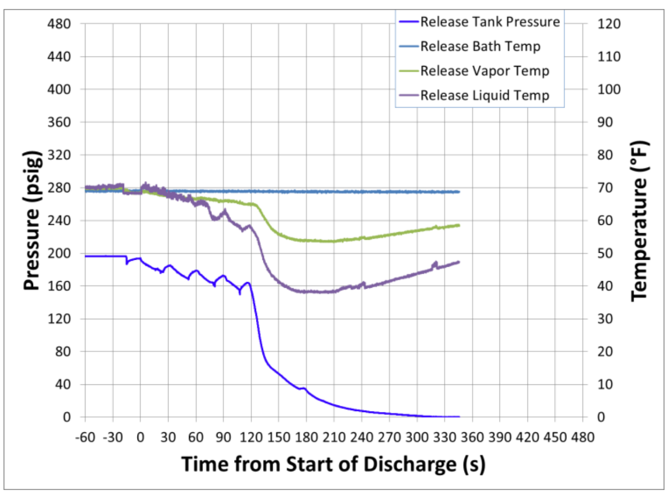
4.6.2.4.4. Term04:

The test parameters for this test were as follows:

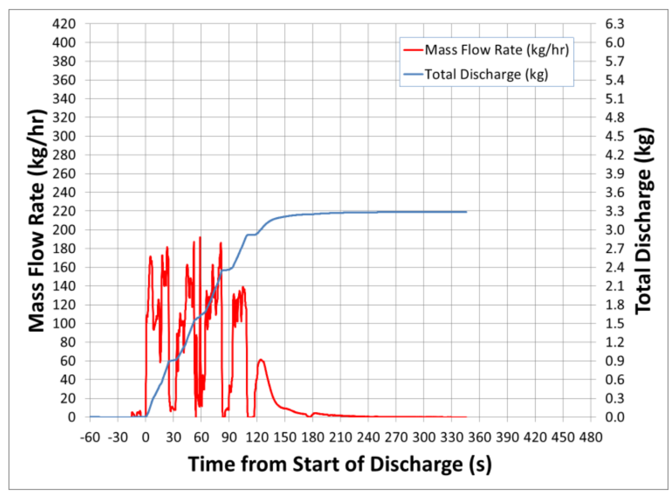
Refrigerant	Initial Release rate (g/s)	Planned Discharge (kg)	Ignition Result
R-32	66	3.85	No ignition

There was no ignition during the test. The molded plug was ejected from the electrical terminal during the refrigerant release. The condenser fan remained operational during the entire test. After the test, the unit was inspected and there was that evidence the oil from the sump of the compressor had been discharged through the hole in the electrical terminal. The oil had been deposited on the interior surfaces of the condenser as well as deposited on the grill fan blades of the condenser fan. During this test there was evidence of electrical interference with the refrigerant release system. This was caused by the close proximity of the high voltage electric arc and the condensing unit.

The test results are presented in Figure 155.



Pressure and Temperature in Release Tank



Refrigerant Release Rate

Noise in Mass Flow Rate was due to interferiance caused by the high voltage ignition source.

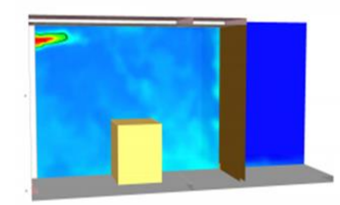
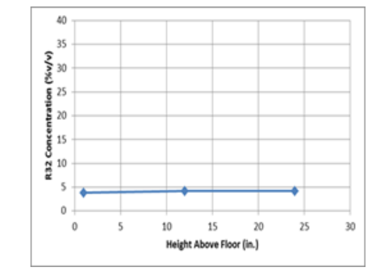
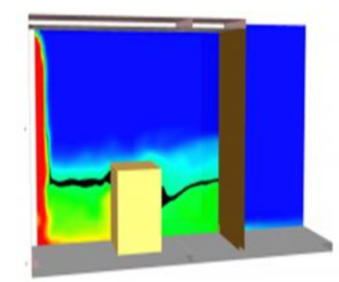
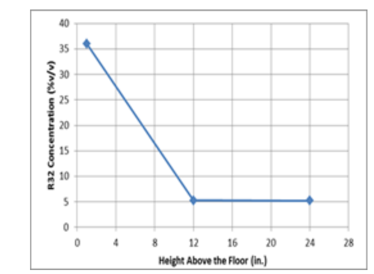
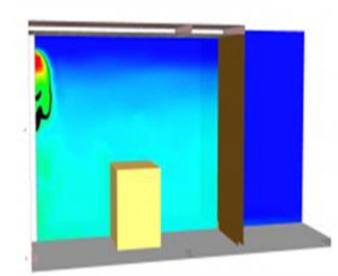
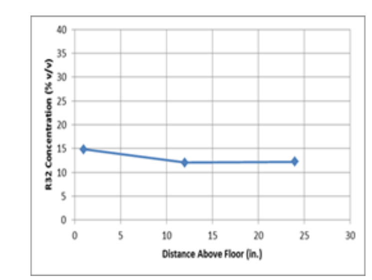
Initial Position of Molded Plug

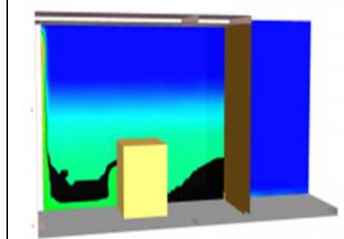
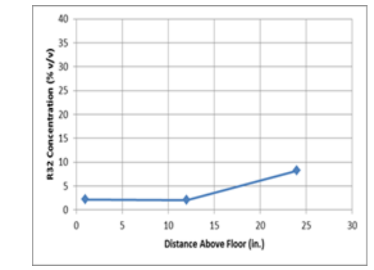
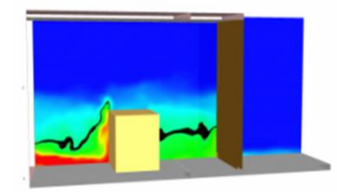
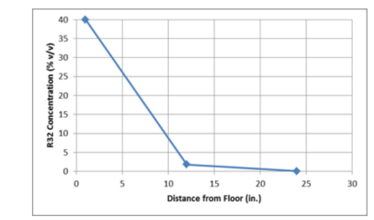
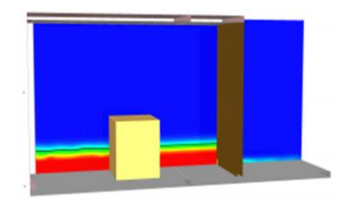
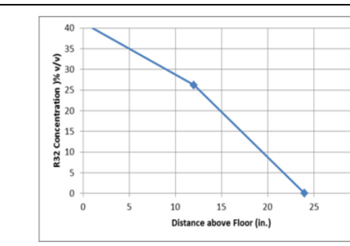
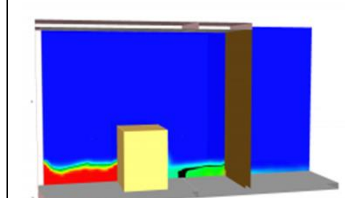
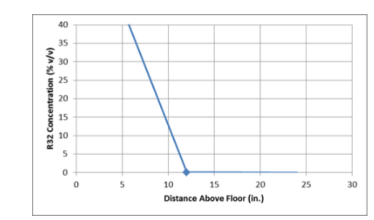
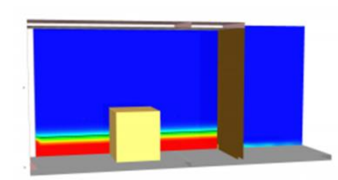
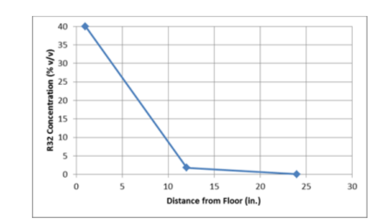
Molded Plug no longer attached to compressor (10s after release)

Release of Refrigerant (40s after release start)

Figure 155 – Data from Term04

Appendix A Comparison of CFD Simulations with Calibration Test Experiments

CFD Simulation Number	Comparable Calibration Test Number	Flow Characteristics	Result from CFD	Results from Test and Discussion	Still Scene from CFD Simulation	Refrigerant Concentration from Test at Ignition
1 **Release Rate:** **100 g/s** **Opening Size:** **50 x 50 mm** **Location:** **2.2 m height**	Cal6 **Release Rate: 100 g/s** **Opening Size: 25 mm dia.** **Location:** **2.2 m height**	High velocity release	Refrigerant release is a jet mixes well in the test room with ambient air resulting in concentrations bellow lower flammability limit	Refrigerant release as a jet and mixes well in the test room with ambient air resulting in concentrations below lower flammability limit. There is no ignition of the refrigerant.		
2 **Release Rate:** **13.5 g/s** **Opening Size:** **50 x 50 mm** **Location:** **2.2 m height**	Cal5 **Release Rate: 13.5 g/s** **Opening Size: 25 mm dia.** **Location:** **2.2 m height**	Low velocity release	Refrigerant mixes with ambient air at the bottom of the room resulting in a flammable mixture.	There is a region of high concentration of refrigerant at the bottom of the test room. Ignition of the refrigerant occurs.		
3 **Release Rate:** **100 g/s** **Opening Size:** **300 x 300 mm** **Location:** **2.2 m height**	Cal13 **Release Rate: 100 g/s** **Opening Size: 356 mm dia.** **Location:** **2.2 m height**	Low velocity release	Refrigerant flow as a slow jet and mixes with the ambient air resulting in concentrations below the lower flammability limits.	The refrigerant flows into the room and develops concentration above the lower flammability limit. Liquid refrigerant runs down the wall and forms a pool on the floor. Ignition of the refrigerant occurs. A comparison of the video shows a jet with greater horizontal velocity than the CFD simulation. The CFD model assumes single-phase gaseous flow while the video shows two-phase flow. Additionally, the video shows the mist coming out of the lower ¼ of the 356 mm duct leading to higher velocity. Further, some refrigerant remained in the 356 mm dia. duct. This contributed to lower concentration in the test room.		

CFD Simulation Number	Comparable Calibration Test Number	Flow Characteristics	Result from CFD	Results from Test and Discussion	Still Scene from CFD Simulation	Refrigerant Concentration from Test at Ignition
4 **Release Rate: 13.5 g/s** **Opening Size:** **300 x 300 mm** **Location:** **2.2 m height**	Cal12 **Release Rate: 13.5 g/s** **Opening Size: 356 mm dia.** **Location:** **2.2 m height**	Very low velocity release	Refrigerant flow pools at the floor of the test room resulting a rich refrigerant mixture.	Refrigerant mixes with air as it is released, and creates a mixture with concentration below the flammability limits. Some refrigerant remained in the 356 mm dia. duct. This contributed to lower concentration in the test room.		
5 **Release Rate:** **100 g/s** **Opening Size:** **50 x 50 mm** **Location:** **0.2 m height**	Cal08, Cal09 **Release Rate: 100 g/s** **Opening Size:** **25 mm dia.** **Location:** **0.2 m height**	High velocity release	The release jet interacts with the obstruction to develop flammable mixture above the test room floor.	The refrigerant release interacts with the obstruction rich mixture at the floor and concentration between flammability limits within 12 inches above the floor. Ignition occurs.		
6 **Release Rate: 13.5 g/s** **Opening Size:** **50 x 50 mm** **Location:** **0.2 m height**	Cal7 **Release Rate: 13.5 g/s** **Opening Size:** **25 mm dia.** **Location:** **0.2m height**	Low velocity release	The refrigerant pools immediately on release resulting in a rich mixture at the floor and small volume of flammable mixture approximately 12 inches above the floor.	Refrigerant interacts with the obstruction and a rich mixture at the floor. Ignition occurs.		
7 **Release Rate:** **100 g/s** **Opening Size:** **300 x 300 mm** **Location:** **0.2 m height**	Cal11 **Release Rate:** **100 g/s** **Opening Size:** **356 mm dia.** **Location:** **0.2 m height**	Low velocity release	The refrigerant pools immediately on release resulting in a rich mixture at the floor and small volume of flammable mixture approximately 12 inches above the floor.	Refrigerant interacts with the obstruction and a rich mixture at the floor. Ignition occurs.		
8 **Release Rate:** **13.5 g/s** **Opening Size:** **300 x 300 mm** **Location:** **0.2 m height**	Cal10 **Release Rate:** **13.5 g/s** **Opening Size:** **356 mm dia.** **Location:** **0.2 m height**	Very low velocity release	The refrigerant pools immediately on release resulting in a rich mixture at the floor and small volume of flammable mixture approximately 12 inches above the floor.	Refrigerant interacts with the obstruction and a rich mixture at the floor. Ignition occurs.		

Appendix B Task 1 Test Data Summary

In the following tables, temperatures are color coded according to the following legend:

Range	Example
0 – 105 °F	97
105 – 400 °F	243
400°F and higher	1152

Calibration Tests

	Test Conditions										Results					
Test Number	Refrigerant	Target Release Rate (g/s)	Target Concentration Level (Well-mied)	Temperature and Humidity (°F/ %RH)	Obstruction	Lubricating Oil (%)	Release Height (m)	Release Opening Size (mm Dia.)	Total Mass Released (kg)	Average Release Rate (g/s)	Max Pressure (mm Hg)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	Ignition	Max Temp (°F)	Max Temp Location
Cal05	R-32	13.5	50	91 °F/70%RH	Yes	0	2.2	25	3.26	13.6	0.664	336	243	Yes	479	B2 - 12
Cal06	R-32	100	50	91 °F/70%RH	Yes	0	2.2	25	3.35	83.8	0.008	97	95	No	97	E1 - 92
Cal07	R-32	13.5	50	91 °F/70%RH	Yes	0	0.2	25	3.25	13.8	3.947	914	672	Yes	1306	A3 - 18
Cal08	R-32	100	50	91 °F/70%RH	Yes	0	0.2	25	3.32	79	2.656	1458	1197	Yes	1540	B2 - 84
Cal09	R-32	100	50	91 °F/70%RH	Yes	0	0.2	25	3.34	81.6	4.476	1241	882	Yes	1688	A3 - 8
Deflagration vent method changed																
Test Number	Refrigerant	Target Release Rate (g/s)	Target Concentration Level (Well-mied)	Temperature and Humidity (°F/ %RH)	Obstruction	Lubricating Oil (%)	Release Height (m)	Release Opening Size (mm Dia.)	Total Mass Released (kg)	Average Release Rate (g/s)	Max Pressure (mm Hg)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	Ignition	Max Temp (°F)	Max Temp Location
Cal10	R-32	13.5	50	91 °F/70%RH	Yes	0	0.2	356	3.27	13.8	0.024	431	338	Yes	1183	B2 - 12
Cal11	R-32	100	50	91 °F/70%RH	Yes	0	0.2	356	3.29	80.3	0.04	498	367	Yes	1464	B2 - 18
Cal12	R-32	13.5	50	91 °F/70%RH	Yes	0	2.2	356	3.21	13.5	0.006	98	95	No	101	B2 - 60
Cal13 [1]	R-32	100	50	91 °F/70%RH	Yes	0	2.2	356	3.26	55.2	0.338	1365	1094	Yes	2008	B2 - 8
Cal16	R-32	50	50	91 °F/70%RH	Yes	0	1.8	25	3.28	48.9	0.009	202	187	Yes	1659	B2 - 4
Cal17	R-32	50	50	91 °F/70%RH	Yes	0	1.8	356	3.3	49.2	0.18	762	634	Yes	1477	B2 - 4
Cal18	R-452B	100	50	91 °F/70%RH	Yes	0	0.2	25	3.46	93.4	1.112	1457	1283	Yes	1515	A3 - 12
CAL20	R-32	100	25	91°F / 70%RH	Yes	0	0.2	356	1.93	93.8	0.01	93	91	No	93	E1 - 92

Parametric Tests

	Test Conditions										Results					
Test Number	Refrigerant	Target Release Rate (g/s)	Target Concentration Level (Well-mied)	Temperature and Humidity (°F/ %RH)	Obstruction	Lubricating Oil (%)	Release Height (m)	Release Opening Size (mm Dia.)	Total Mass Released (kg)	Average Release Rate (g/s)	Max Pressure (mm Hg)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	Ignition	Max Temp (°F)	Max Temp Location
PA01	R-452B	100	50	73°F / 50%RH	Yes	0	0.2	25	3.82	98.9	0.15	1802	1498	Yes	>2300*	B2 - 92
PA02	R-452B	100	50	91°F / 70%RH	Yes	0	0.2	25	3.76	97.4	0.66	1805	1521	Yes	1816	B2 - 88
PA03	R-32	100	50	73°F / 50%RH	Yes	0	0.2	25	3.75	101.7	0.36	1479	1250	Yes	1638	B2 - 18
PA04	R-410A	100	50	91°F / 70%RH	Yes	0	0.2	25	3.73	100.8	0.01	95	92	No	102	B2 - 60
PA05	R-32	100	50	91°F / 70%RH	Yes	0	0.2	25	3.75	96.8	0.44	1492	1307	Yes	1552	A3 - 60
PB01	R-32	100	50	91°F / 70%RH	Yes	0	0.2	25	3.89	82	0.39	1500	1367	Yes	1911	A3 - 60
PB02	R-452B	100	50	91°F / 70%RH	Yes	0	0.2	25	3.84	98.1	0.63	1503	1350	Yes	1647	A3 - 60
PB03	R-452B	100	50	91°F / 70%RH	No	0	0.2	25	3.81	104	0.02	295	248	Yes	1104	B2 - 4
PB04	R-32 [1]	100	50	91°F / 70%RH	No	0	0.2	25	3.71	62	0.29	>2300*	1359	Yes	>2300*	A3 - All
PB05	R-410A	100	50	91°F / 70%RH	No	0	0.2	25	3.7	63.4	0.01	104	101	Yes	111	B2 - 60
PB08	R-32	100	25	91°F / 70%RH	No	0	0.2	25	1.94	96.6	0.01	98	96	No	98	D2 - 92
PB09	R-452B	100	25	91°F / 70%RH	No	0	0.2	25	1.87	97.8	0.01	96	94	No	96	D2 - 92
PB10	R-32	100	25	91°F / 70%RH	Yes	0	0.2	25	1.77	96.1	0.01	221	172	Yes	221	B2 - 92
PB11	R-452B	100	25	91°F / 70%RH	Yes	0	0.2	25	1.8	97.8	0.01	121	106	Yes	121	B2 - 92
PB12	R-32	100	50	91°F / 70%RH	No	0	0.2	25	3.49	98.7	0.01	101	99	No	101	D2 - 92
PC07	R-410A	100	50	91°F / 70%RH	No	1.5	0.2	25	3.36	75.3	0.01	101	99	No	101	E3 - 92
PC08	R-410A	100	50	91°F / 70%RH	No	3.0	0.2	25	3.3	81.3	0.01	99	97	No	100	B2 - 60
PC10	R-32	100	50	91°F / 70%RH	No	1.5	0.2	25	3.86	97.3	0.35	1677	1338	Yes	1939	B2 - 18
PC11	R-32	100	50	91°F / 70%RH	No	3.0	0.2	25	3.62	98.8	0.01	134	110	Yes	134	B2 - 92
PC12	R-22	100	50	91°F / 70%RH	No	1.5	0.2	25	4.12	99.1	0.01	99	97	No	99	E1 - 92
PC13	R-22	100	50	91°F / 70%RH	No	3.0	0.2	25	4.26	90.3	0.01	100	98	No	100	E1 - 92
PC14	R-452B	100	50	91°F / 70%RH	No	3.0	0.2	25	3.53	95.4	0.02	97	95	No	97	D2 - 92
PC15	R-452B	100	50	91°F / 70%RH	No	1.5	0.2	25	3.51	90	0.01	98	96	No	101	B2 - 60

* The maximum range of a Type K thermocouple is approximately 2300°F. These experiments reported temperatures as high as 2740°F and are recorded as being greater than 2300°F.

Appendix C Task 2 Test Data Summary

The Discharge Start and Discharge End times reported in the follow tables are with respect to the start of the video tape.

In the following tables, temperatures are color coded according to the following legend:

Range	Example
0 – 105 °F	97
105 – 400 °F	243
400°F and higher	1152

PTAC

Scenario	Test Code	Date	Valid/Invalid	Test Description / Objective	Refrigerant	Intended Discharge Quantity (kg)	Intended Discharge Rate (g/s)	Actual Discharge Quantity (kgs)	Average Discharge Rate (g/s)	Discharge Start (mm:ss)	Discharge End (mm:ss)	Maximum Refrigerant Concentration (%)	Max Pressure (mm Hg)	Max Temp Location	Max Temp (°F)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)
PTAC	PTAC01		Invalid	Equipment shakedown	R-22												
PTAC	PTAC02		Invalid	Equipment shakedown	R-22												
PTAC	PTAC03		Invalid	Equipment shakedown	R-32												
PTAC	PTAC04	2016-10-28	Valid	Measure concentration	R-32	1.81	50	1.98	44.7	02:32	03:43	15.2	0.01	C92	92	91	91
PTAC	PTAC05	2016-10-28	Valid	Measure concentration	R-452B	1.82	50	1.88	48.0	01:28	02:07	9.8	0.01	C92	97	95	95
PTAC	PTAC06	2016-10-28	Valid	Arcs and Candles	R-32	1.81	50	1.87	37.3	00:53	02:28	9.4	0.01	A92	101	98	98
PTAC	PTAC07	2016-10-28	Valid	Arcs and Candles	R-452B	1.82	50	1.92	47.4	01:11	02:07	11.4	0.01	A92	104	97	97
PTAC	PTAC08	2016-10-31	Valid	Arcs and Candles	R-32	1.81	50	2.07	46.6	01:08	02:07	9.8	0.01	C18	106	95	95
PTAC	PTAC09	2016-10-31	Valid	Arcs and pre-lit Candles	R-32	1.81	50	1.78	42.6	00:47	01:25	10.8	0.01	C08	119	97	97
PTAC	PTAC10	2016-10-31	Valid	Arcs and pre-lit Candles	R-452B	1.82	50	1.88	45.2	01:15	02:59	9.6	0.01	C04	120	97	97
PTAC	PTAC11	2016-11-01	Valid	Measure concentration	R-452B	1.82	50	2.06	47.1	00:41	01:36	9.5	0.01	C92	96	93	93
PTAC	PTAC12	2016-11-02	Valid	Measure concentration	R-32	1.81	50	1.96	46.7	04:02	04:54	8.9	0.01	C92	99	96	96

Reach-in Cooler

Scenario	Test Code	Date	Valid/Invalid	Test Description / Objective	Refrigerant	Intended Discharge Quantity (kg)	Intended Discharge Rate (g/s)	Actual Discharge Quantity (kgs)	Average Discharge Rate (g/s)	Discharge Start (mm:ss)	Discharge End (mm:ss)	Maximum Refrigerant Concentration (%)	Max Pressure (mm Hg)	Max Temp Location	Max Temp (°F)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)
Reach-in	Cooler01	2016-11-09	Valid	Release inside cooler then open lower door	R-455A	0.5	10	0.60	6.1	01:04	02:12	5.8	0.91	A12	685	274	238
Reach-in	Cooler02	2016-11-09	Valid	Release inside cooler then open lower door	R-457A	0.5	10	0.50	9.0	01:25	02:19	3.2	1.49	A04	859	437	343
Reach-in	Cooler03	2016-11-10	Valid	Release inside cooler then open lower door	R-457A	0.3	10	0.32	4.1	01:05	01:32	3.7	1.35	B12	119	94	93
Reach-in	Cooler04	2016-11-10	Valid	Release inside cooler then open lower door	R-457A	0.4	10	0.40	5.0	00:53	01:28	2.3	0.76	A04	446	281	222

Walk-in Cooler

Scenario	Test Code	Date	Valid/Invalid	Test Description / Objective	Refrigerant	Intended Discharge Quantity (kg)	Intended Discharge Rate (g/s)	Actual Discharge Quantity (kgs)	Average Discharge Rate (g/s)	Discharge Start (mm:ss)	Discharge End (mm:ss)	Maximum Refrigerant Concentration (%)	Max Pressure (mm Hg)	Max Temp Location	Max Temp (°F)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)
Walk-in	Walkin01	2016-11-14	Invalid	Return Bend Door Closed	R-455A	5.4	50	2.86	41.7	01:04	02:00	7.4	0.02	C12	172	130	107
Walk-in	Walkin02	2016-11-14	Invalid	Return Bend Door Closed	R-457A	2.7	50	3.51	37.1	00:53	02:38	7.7	0.16	A88	1667	1517	1312
Walk-in	Walkin03	2016-11-15	Invalid	Return Bend Door Open	R-455A	5.4	50	2.83	44.1	01:12	02:15	8.6	0.01	C92	89	89	88
Walk-in	Walkin04	2016-11-15	Invalid	Return Bend Door Open	R-457A	2.7	50	5.23	49.2	00:43	02:30	24.4	0.13	C92	1397	1397	1231
Walk-in	Walkin05	2016-11-15	Invalid	Coil Face Door Closed	R-455A	5.4	50	2.80	44.7	00:32	01:34	3.4	0.01	B84	90	89	89
Walk-in	Walkin06	2016-11-15	Invalid	Coil Face Door Closed	R-457A	2.7	50	5.26	45.1	00:36	02:32	7.0	0.17	C88	1513	1183	1005
Walk-in	Walkin07	2016-11-15	Invalid	Coil Face Door Open	R-457A	2.7	50	5.23	44.1	00:32	02:32	5.5	0.01	A08	90	88	87
Walk-in	Walkin08	2016-12-08	Valid	Return Bend Door Closed	R-455A	5.4	50	5.25	46.3	01:04	02:58	10.2	0.00	C88	1735	1588	1363
Walk-in	Walkin09	2016-12-08	Valid	Return Bend Door Closed	R-457A	2.7	50	2.84	48.7	00:33	01:31	6.7	0.01	C04	354	180	151
Walk-in	Walkin10	2016-12-08	Valid	Return Bend Door Open	R-457A	2.7	50	2.91	45.6	00:51	02:11	7.2	0.01	C04	142	114	110
Walk-in	Walkin11	2016-12-08	Valid	Return Bend Door Open	R-455A	5.4	50	5.25	38.9	01:03	03:26	8.3	0.01	A92	1541	1541	1436
Walk-in	Walkin12	2016-12-09	Valid	Coil Face Door Closed	R-455A	5.4	50	4.95	36.6	00:33	03:13	8.6	0.00	A04	95	89	88
Walk-in	Walkin13	2016-12-09	Valid	Coil Face Door Closed	R-457A	2.7	50	3.06	46.9	00:37	03:00	4.4	0.00	C60	92	88	87
Walk-in	Walkin14	2016-12-09	Valid	Coil Face Door Open	R-455A	5.4	50	5.20	43.9	01:29	03:30	5.4	0.00	C04	100	93	91

Residential Split System

Scenario	Test Code	Date	Valid Invalid	Test Description / Objective	Refrigerant	Intended Discharge Quantity (kg)	Intended Discharge Rate (g/s)	Actual Discharge Quantity (kgs)	Average Discharge Rate (g/s)	Discharge Start (mm:ss)	Discharge End (mm:ss)	Maximum Refrigerant Concentration (%)	Max Pressure (mm Hg)	Max Temp Location	Max Temp (°F)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)
Residential A-Coil Leak	Res01	2016-11-29	Invalid	with mitigation @30 seconds	R-32	3.83	50	1.31	13.8	00:59	02:33	10.5	0.02	B08	1190	213	160
Residential A-Coil Leak	Res02	2016-11-29	Valid	with mitigation @30 seconds	R-32	3.83	50	3.91	47.1	00:34	02:09	14.4	0.05	B12	1725	334	234
Residential A-Coil Leak	Res03	2016-11-29	Valid	with mitigation @30 seconds	R-452B	4.2	50	4.27	47.4	01:31	03:01	7.4	0.03	B04	920	417	229
Residential A-Coil Leak	Res04	2016-11-30	Valid	No mitigation	R-32	1.8	50	1.82	46.4	00:43	01:21	10.9	0.03	B08	1610	296	221
Residential A-Coil Leak	Res05	2016-11-30	Valid	No mitigation	R-452B	1.85	50	1.87	46.3	00:54	01:34	10.1	0.04	B12	1459	306	219
Residential Service Error	Res06	2016-11-30	Valid	Refrigerant + 30 g oil	R-410A	1.8	Natural Decay	1.81	29.0	00:36	01:45	2.5	0.00	C92	93	93	92
Residential Service Error	Res07	2016-11-30	Valid	Refrigerant + 30 g oil	R-32	1.8	Natural Decay	1.57	28.1	00:29	01:36	3.2	0.00	A84	92	91	90
Residential Service Error	Res08	2016-11-30	Valid	Refrigerant + 30 g oil	R-452B	1.85	Natural Decay	1.35	18.4	00:31	01:44	**Data Acquisition Failure (no Data)**					

Commercial Kitchen

Scenario	Test Code	Date	Valid/Invalid	Test Description / Objective	Refrigerant	Intended Discharge Quantity (kg)	Intended Discharge Rate (g/s)	Actual Discharge Quantity (kgs)	Average Discharge Rate (g/s)	Discharge Start (mm:ss)	Discharge End (mm:ss)	Maximum Refrigerant Concentration (%)	Max Pressure (mm Hg)	Max Temp Location	Max Temp (°F)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)
Kitchen	Kitchen01	2016-12-05	Valid	Mitigation @30s	R-452B	7.07	100	7.10	93.0	01:01	02:20	5.5	0.03	B08	151*	88	85
Kitchen	Kitchen02	2016-12-06	Valid	Mitigation @30s	R-32	6.89	100	6.92	83.0	00:41	02:08	5.3	0.02	B12	173*	83	81
Kitchen	Kitchen03	2016-12-06	Valid	Mitigation @60s	R-452B	7.07	100	7.09	81.9	00:35	02:06	5.3	0.01	B18	159*	86	84
Kitchen	Kitchen04	2016-12-06	Invalid	Mitigation @60s	R-32	6.89	100	6.74	20.4	01:08	06:43	4.9	0.01	B12	162*	83	81
Kitchen	Kitchen05	2016-12-07	Valid	Mitigation @60s	R-32	6.89	100	6.90	89.8	00:42	02:03	4.6	0.01	D48	98	87	86

* - These high temperatures are suspect because the videos show no signs of combustion. Electromagnetic interference is suspected at Location B’s thermocouple tree.

Hermetic Electrical Pass-Through Terminal Failure

Scenario	Test Code	Date	Valid/Invalid	Test Description / Objective	Refrigerant	Intended Discharge Quantity (kg)	Intended Discharge Rate (g/s)	Actual Discharge Quantity (kg)	Average Discharge Rate (g/s)	Discharge Start (mm:ss)	Discharge End (mm:ss)	Maximum Refrigerant Concentration (%)	Max Pressure (mm Hg)	Max Temp Location	Max Temp (°F)	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	Result
Hermetic Electrical Pass-Through Terminal Failure	Term01	2016-12-06	Invalid	natural decay	R-410A	5.25	66 Initial	3.93	31.7	00:43	03:34	Not Used	Not Used	Not Used	Not Used	Not Used	Not Used	No Ignition
Hermetic Electrical Pass-Through Terminal Failure	Term02	2016-12-06	Valid	natural decay	R-452B	4.24	66 Initial	3.38	30.2	00:58	03:30	Not Used	Not Used	Not Used	Not Used	Not Used	Not Used	Ignition
Hermetic Electrical Pass-Through Terminal Failure	Term03	2016-12-06	Valid	natural decay	R-410A	5.25	66 Initial	3.90	15.6	00:42	06:41	Not Used	Not Used	Not Used	Not Used	Not Used	Not Used	No Ignition
Hermetic Electrical Pass-Through Terminal Failure	Term04	2016-12-06	Valid	natural decay	R-32	3.85	66 Initial	3.28	23.3	01:10	04:11	Not Used	Not Used	Not Used	Not Used	Not Used	Not Used	No Ignition

Appendix D Test Instrumentation and Equipment

Table 45 summarizes the instrumentation and equipment used in the Task 1 and Task 2 test programs. The following sections provide more detail on each item in the table.

Table 45 - Instrumentation

Instrumentation Name	Instrumentation Code	Manufacturer	Range	Accuracy
Thermocouple [1]	TC\GG-K-24-SLE	Omega	minus 200 °C to 1250 °C	±2 °C
Thermocouple [1]	TC\TJ36-CAXL-18U-48	Omega	minus 200 °C to 1250 °C	±2 °C
Refrigerant Electronics and Refrigerant Sensor [2]	GA\Henze-Hauck Electronics GA\Refrigerant Sensor	Henze-Hauck	0-100% concentration	±3 %
NI Data Acquisition System [1]	DAS\NI Data Acquisition System	National Instruments	Multi-Range	±0.1%
Pressure Transducer [1]	PT\TD1000	Transducers Direct	0-500 psig	±0.5%
Pressure Transducer [1]	PT\220DD 10 Torr	MKS Instruments	0-10 mmHg	±0.15 %
Pressure Transducer [1]	PT\220DD 1 Torr	MKS Instruments	0-1 mmHg	±0.15 %
Mass Flow Control System [2]	Other\MassFlow Control System	Hallfield Controls	0-600 kg/hr	±3 %
Scale [1]	SCL\7000xl	Doran	0-500 lbm	±0.2 lbm
Temp/Hum/Pres probe [1]	THI\THWD-5	Amprobe	14-140°F; 0-100% RH	±1 °F ±3 % RH

[1] – Accuracy from suppliers information

[2] – Accuracy from in-house validation/calibration

AHRTI Supplied Equipment	Manufacturer
Commercial Kitchen Roof-Mounted Fan Coil	Lennox
PTAC	Goodman
Air Handling/coil Unit	Goodman
Outdoor Condenser	Goodman
Compressor	Emerson
Reach-in Cooler	Manitwoc
Walk-in Unit Cooler	Heatcraft

Instrumentation

Thermocouple wire

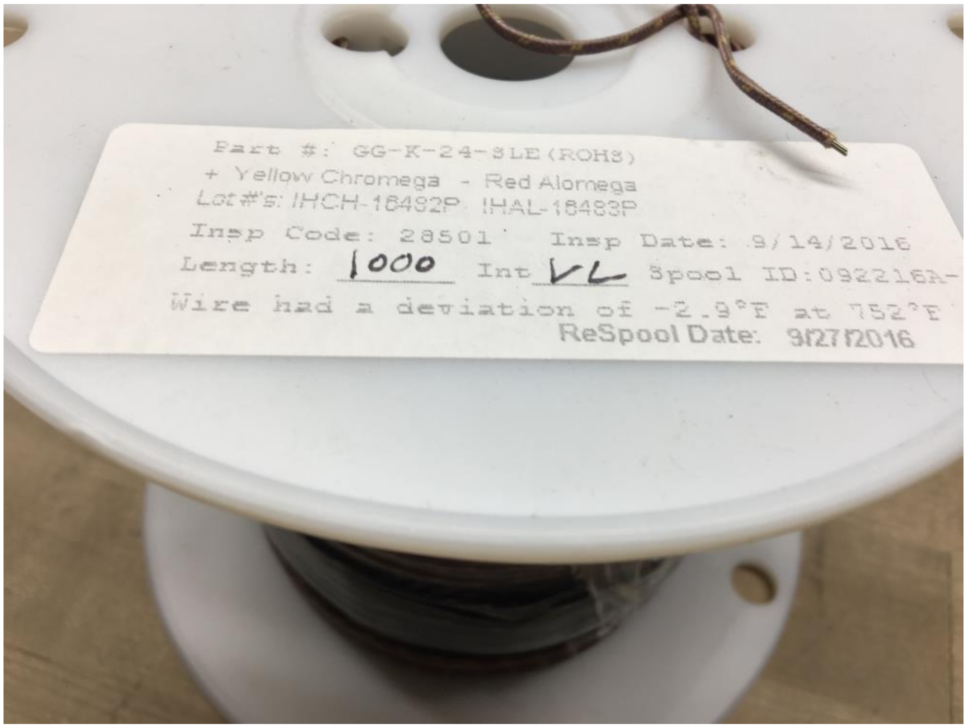


Figure 156 - TC\GG-K-24-SLE

24-gauge Type K thermocouple wire was used to create bare bead TC's for use in various monitoring locations. The response time is 3.0 seconds (63% of step change). Reference: http://www.omega.com/techref/ThermocoupleResponseTime.html

Thermocouple, shielded probe

Figure 157 - TC\TJ36-CAXL-18U-48

Ungrounded 1/8 inch diameter type K thermocouples were used to measure temperatures in the release and pressure tanks as well as the surrounding water baths.

Refrigerant Electronics

Figure 158 - GA\Henze-Hauck Electronics

The Henze-Hauck electronics package provides power for heating to the sensor and processes the signal. Four separate systems, one accompanying each sensor, were in use.

Refrigerant Sensor

Figure 159 - GA\Refrigerant Sensor

The Henze-Hauck refrigerant sensor outputs a millivolt signal from a bridge circuit that responds to differences in gas conductivity. The sensors were calibrated for each refrigerant used in the test program.

NI Data Acquisition System

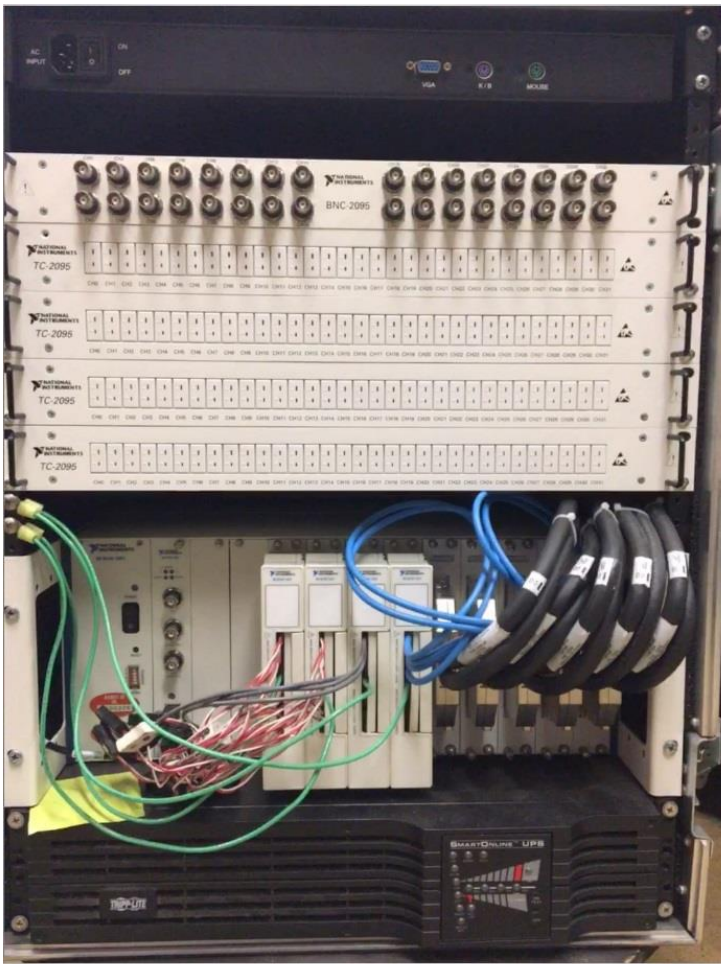


Figure 160 - DAS\NI Data Acquisition System

The data acquisition system contains four TC-2095 32-channel cold-junction compensated thermocouple input panels; One BNC-2095 32 channel channel cold-junction compensated thermocouple input panel, and four SXCI-1327 modules supporting up to 300 V inputs.

Pressure Transducer, 0-500 psig

Figure 161 - PT\TD1000

Pressure transducers were used on the Release and Pressurizer tanks.

Pressure Transducer, 10 Torr

Figure 162 - PT\220DD 10 Torr

The 10 Torr pressure transducers were used to monitor the pressure difference between the test room and various locations. One instrument was later used to monitor differential pressure across the blowers (Residential and Kitchen scenarios).

Pressure Transducer, 1 Torr

Figure 163 - PT\220DD 1 Torr

The 1 Torr pressure transducer monitored the pressure difference between the ISO room and the recovery box.

Mass Flow Control System

Figure 164 - Other\Mass Flow Control System

The mass flow control system was used to control and record the flow of refrigerant.

Scale, 0-500 lbs

Figure 165 - SCL\7000xl

The 7000xl scale was used to record release and pressurizer tank weights before and after filling and also after release weight.

Temp/Hum/Pres probe

Figure 166 - THI\THWD-5

Handheld temperature humidity probe used to determine humidity at the beginning of each test.

AHRTI Supplied Equipment

Commercial Kitchen Roof Top Unit

Figure 167 – Rooftop Kitchen Unit

PTAC

Figure 168 – PTAC Unit

Air Handling/coil Unit

Figure 169 – Residential HVAC

Outdoor Condenser

Figure 170 – Outdoor Condenser and Compressor (Hermetic Electrical Pass-Through Terminal Failure Tests)

Compressor

Figure 171 – Outdoor Compressor (Hermetic Electrical Pass-Through Terminal Failure Tests)

Reach-in Cooler

Figure 172 – Reach-in Cooler

Walk-in Cooler

Figure 173 – Walk-in Unit Cooler

Appendix E Walk-in Cooler Scenario (Tests 1 through 7)

Refrigerant Release

In walk-in tests 1 through 7, the release quantities were correctly calculated, but an operator error led to incorrect discharge amounts of R-457A and R-455A. The refrigerant release quantities were based on $13\ m^3 \times LFL\ \frac{kg}{m^3}$ for R-455A and R-457A. The planned quantities for release were 5.4 kg for R-455A and 2.7 kg for R-457A, but the actual release amounts were reversed. These release quantities were approximately 7*LFL for R-455A and 26* LFL for R-457A. While the discharge amounts were incorrect, the tests are variations that reveal useful information.

The dimensions of the room were 12x14x8 feet resulting in an internal volume of 38 m^3 (1344 ft^3). The release in all cases was set to 50 g/s through a 3/8 inch diameter copper tube. The length of the tube was approximately 5 meters and was attached to a 1 by ½ inch reducer at the exit of the mass flow control valve. Other variables in this scenario included the position of the door (open or closed) and the location of the discharge tube (near a return bend or in the coil face).

The test matrix showing all of these factors is presented in Table 46.

Table 46 – Walk-in Cooler Experimental Matrix

Refrigerant	Test Number	Door Condition	Leak Location	Planned Discharge (kg)	Actual Discharge (kg) [1]	Discharge Rate (g/s)
R-455A	Walkin01	Closed	Return Bend	5.4	2.86	50
R-457A	Walkin02	Closed	Return Bend	2.7	3.51	50
R-455A	Walkin03	Open	Return Bend	5.4	2.83	50
R-457A	Walkin04	Open	Return Bend	2.7	5.23	50
R-455A	Walkin05	Closed	Coil Face	5.4	2.80	50
R-457A	Walkin06	Closed	Coil Face	2.7	5.26	50
R-457A	Walkin07	Open	Coil Face	2.7	5.23	50

Note: [1] Operator error led to incorrect discharge amounts.

Test Procedure

The same procedure as in tests Walkin08 through Walkin14 was used to initiate each test as follows:

1. Confirm pressurizer and release refrigerant tank pressures and temperatures.
2. Develop vacuum (less than 1mm Hg) in piping connecting the pressure and release tanks as well between the release tank and flow meter.
3. Confirm the walk-in cooler temperature and humidity were at 91±3°F and 70±5% relative humidity.
4. Light the candles, turn on spark, and turn off the lab HVAC and humidity systems.
5. Initiate data acquisition and video capture 1 minute prior to discharging refrigerant.

6. Open the valve between the pressure and release tanks, and hold for 5 seconds.
7. Open the valve between release tank and the flow meter and hold for 5 seconds.
8. Open the control valve to initiate refrigerant discharge through the mass flow meter.
9. Continue to collect data until all flaming has ceased for at least 2 minutes.
10. Vent the test room.

After each test, the test facility was exhausted through UL's smoke abatement system, and the conditions in the facility were monitored with open path gas FT-IR. Staff re-entered the test facility for the next only after the gas FT-IR indicated normal ambient conditions.

Summary of Findings – Walk-in Cooler Tests with incorrect release amounts

Because of the incorrect release amounts all but the last test with R-457A resulted in a large ignition event. One R-455A test showed a short duration ignition at the floor level, while the other two R-455A tests resulted in no ignition. These results can be compared with the tests Walkin08 –Walkin14.

As with other task 2 experiments, the tea candles were sometimes extinguished by either high local refrigerant concentration or the combination of the cooling effect and movement of air.

Results

A summary of test results are presented in Table 47 and Table 48.

Table 47 – Walk-in Scenario Discharge Mass, Rate, and Maximum Concentration

Refrigerant	Test Number	Measured Discharge (kg)	Measured Rate (g/s)	Maximum Refrigerant Concentration (%)
R-455A	Walkin01	2.86	41.7	7.4
R-457A	Walkin02	3.51	37.1	7.7
R-455A	Walkin03	2.83	44.1	8.6
R-457A	Walkin04	5.23	49.2	24.4
R-455A	Walkin05	2.80	44.7	[1] 3.4
R-457A	Walkin06	5.26	45.1	7.0
R-457A	Walkin07	5.23	44.1	5.5

Note: [1] The sensor lines were clogged as a result of the previous test. The value represents the residual concentration trapped in the sensor.

Table 48 – Walk-in Scenario Summary (incorrect planned discharge)

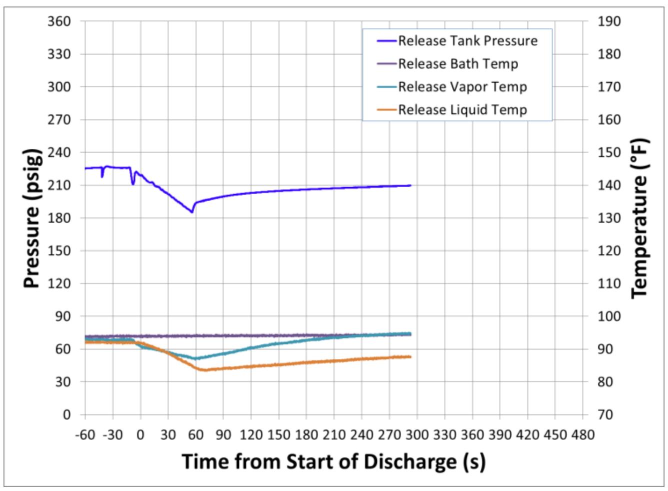
Refrigerant	Test Number	Door Condition	Leak Location	Max Pressure (mmHg)	Max Temperature and Location (°F) /Location	Max Ceiling Temp (°F)	Max Ave Ceiling Temp (°F)	Result
R-455A	Walkin01	Closed	Return Bend	0.02	172 / C12	130	107	Local Ignition
R-457A	Walkin02	Closed	Return Bend	0.16	1667 / A88	1517	1312	Ignition
R-455A	Walkin03	Open	Return Bend	0.01	89 / C92	89	88	No Ignition
R-457A	Walkin04	Open	Return Bend	0.13	1397 / C92	1397	1231	Ignition
R-455A	Walkin05	Closed	Coil Face	0.01	90 / B84	89	89	No Ignition
R-457A	Walkin06	Closed	Coil Face	0.17	1513 / C88	1183	1005	Ignition
R-457A	Walkin07	Open	Coil Face	0.01	90 / A08	88	87	No Ignition

WALKIN01:

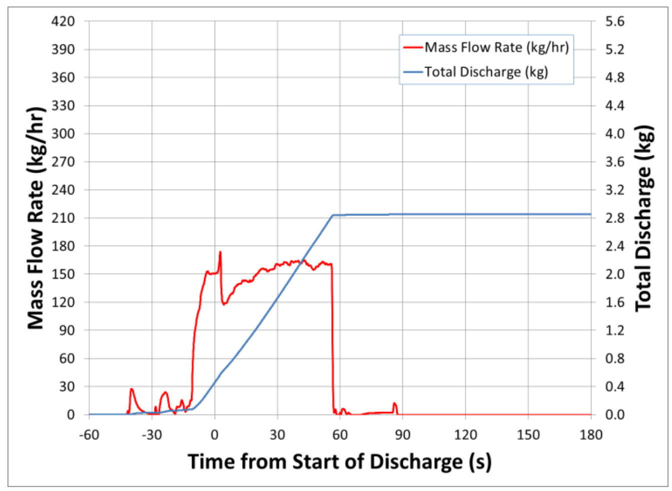
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Actual Discharge (kg)	Door Position	Leak Location	Ignition Result
R-455A	50	2.86	Closed	Return Bend	Local Ignition

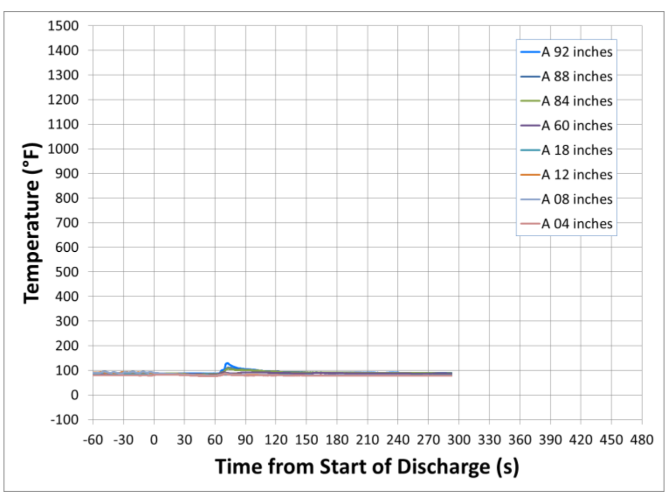
Selected data from this test are shown in Figure 174.



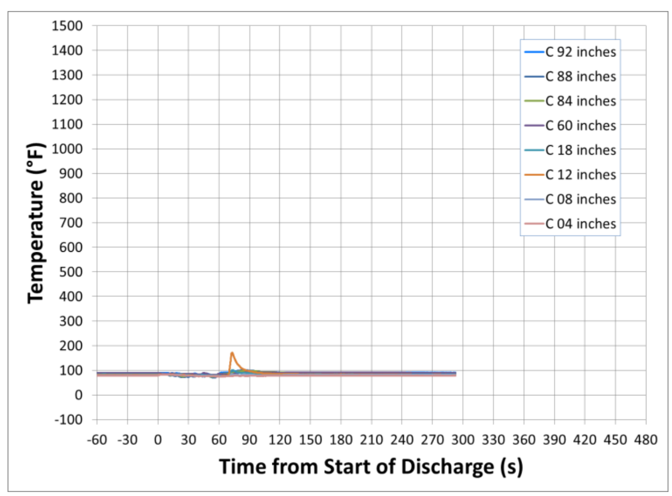
Pressure and Temperature in the Release Tank



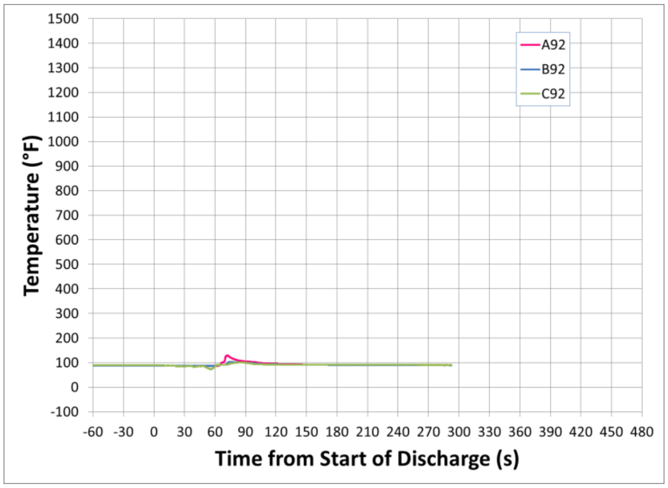
Refrigerant Release Rate



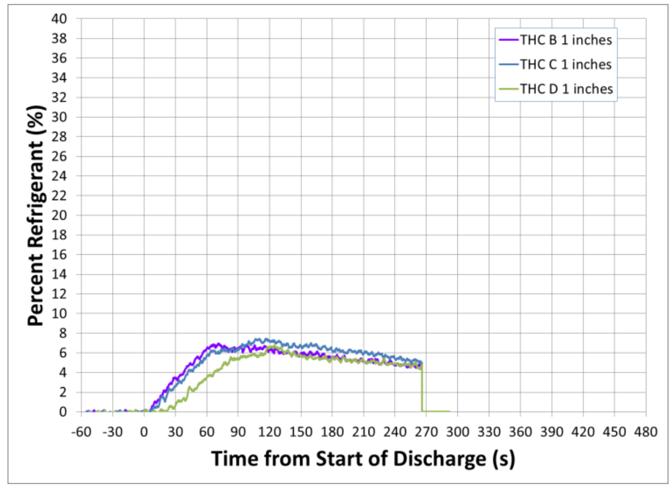
Temperature at Location A



Temperature at Location C



Temperature at 92 in. height above the floor



Refrigerant Concentration

Floor level view at 56 seconds after the start of the discharge. Location C is in the foreground. Flaming lasted was sporadic over a period of 12 seconds.

Local ignition at Location A at 64 seconds after the start of discharge. Flaming lasted 11 seconds. Flames traveled away from the thermocouple tree.

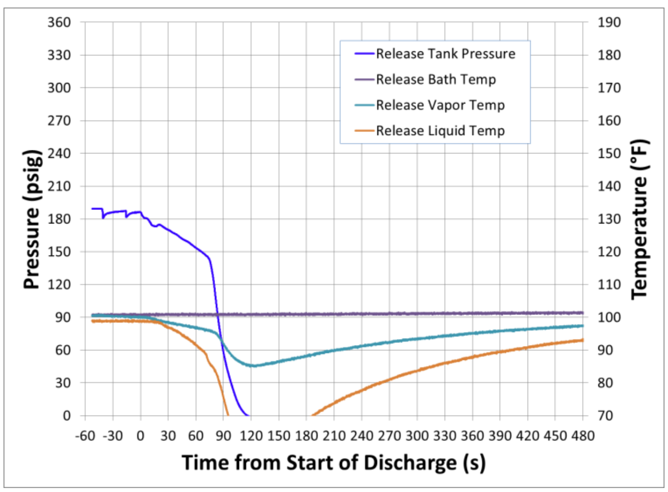
Figure 174 – Data from WALKIN01

WALKIN02:

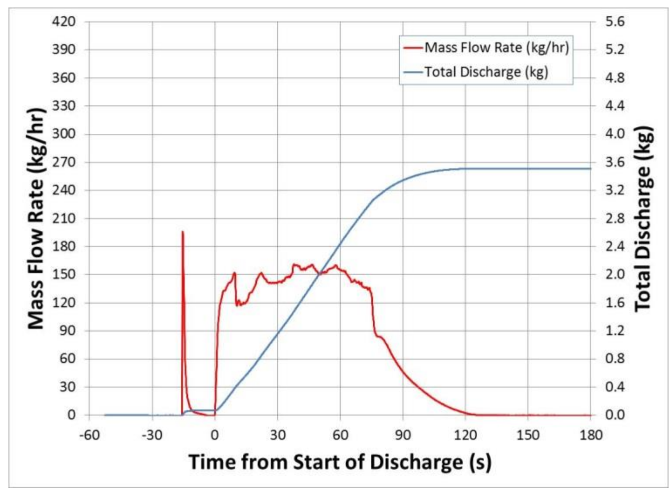
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Actual Discharge (kg)	Door Position	Leak Location	Ignition Result
R-457A	50	3.51	Closed	Return Bend	Ignition

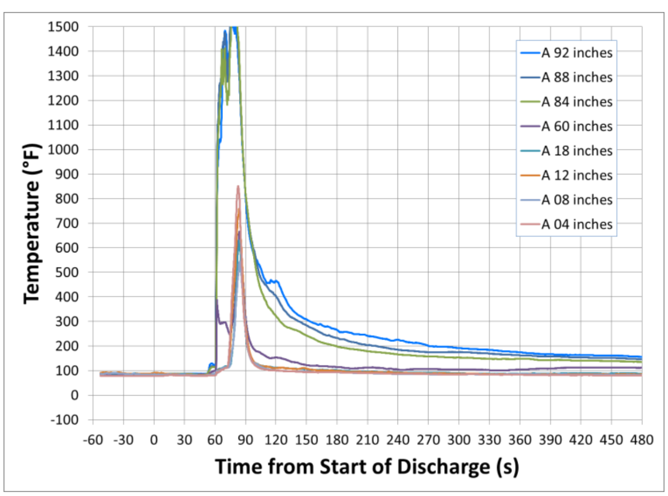
The pressurizer was not used in this experiment. The release tank pressure dropped to near atmospheric within 120 seconds of the start of the discharge. Only 3.5 kg of the planned 5.2 kg discharge was completed. Selected data from this test are shown in Figure 175.



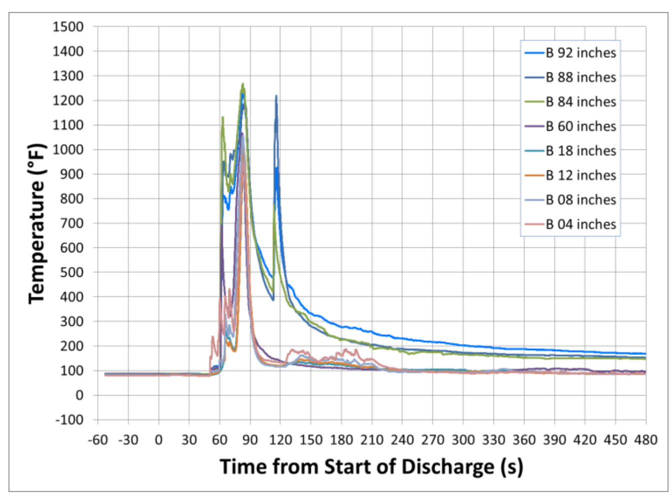
Pressure and Temperature in the Release Tank



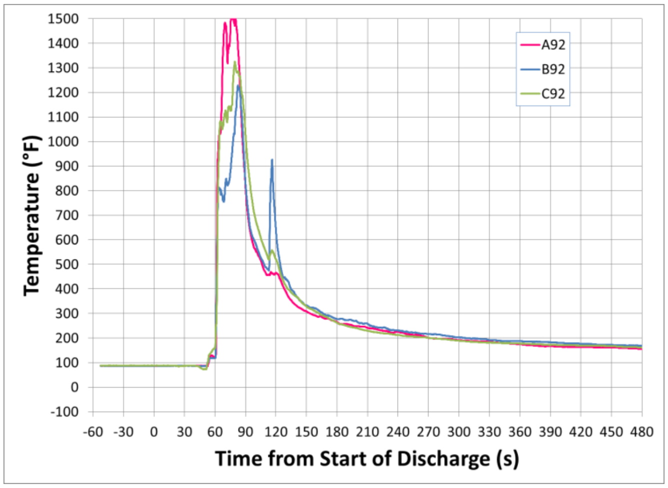
Refrigerant Release Rate



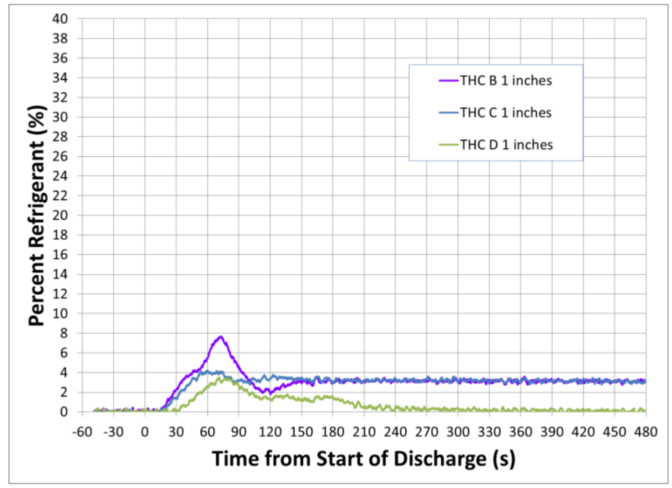
Temperature at Location A



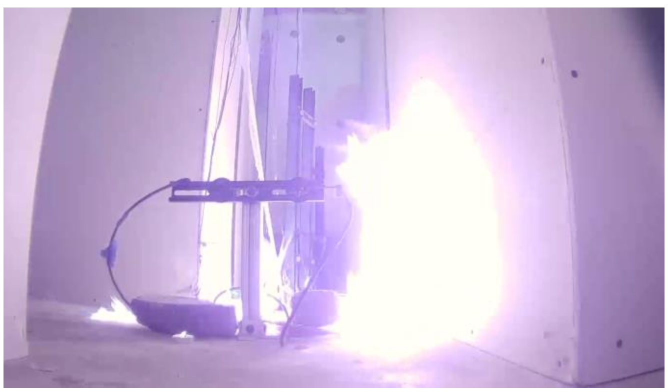
Temperature at Location B



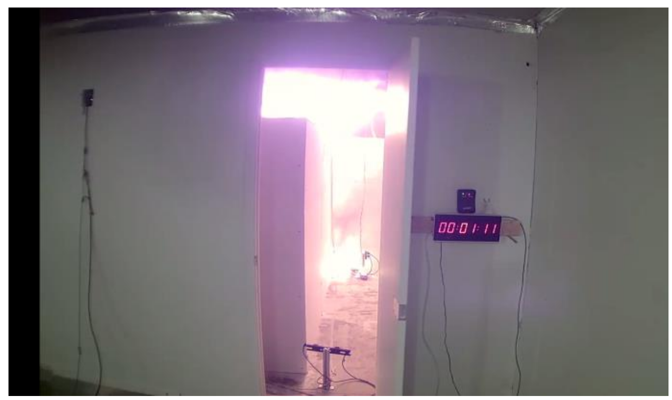
Temperature at 92 in. height above the floor



Refrigerant Concentration



Floor level view at 46 seconds after the start of the discharge. Location C is in the foreground. At 57 seconds the flames reached the ceiling level. Flaming lasted for a total of 87 seconds.



The latch on the door was disabled in order to use the door as a deflagration vent. The door was forced open at 59 seconds after the start of the discharge.

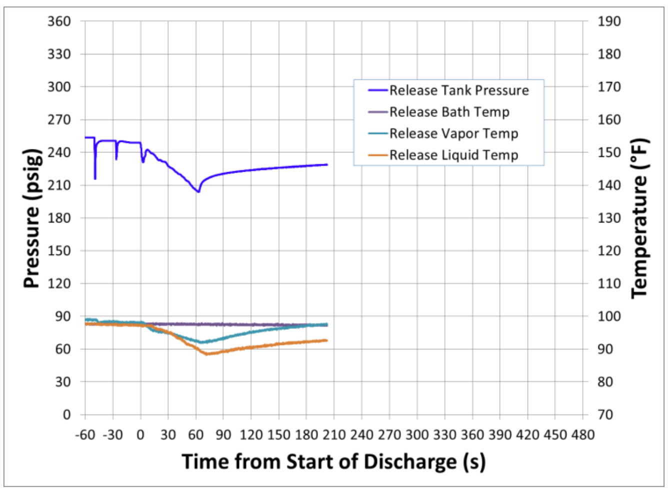
Figure 175 – Data from WALKIN02

WALKIN03:

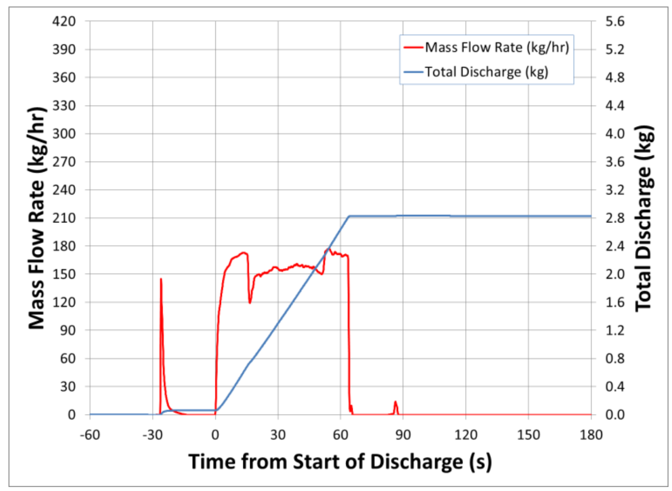
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Actual Discharge (kg)	Door Position	Leak Location	Ignition Result
R-455A	50	2.83	Open	Return Bend	No Ignition

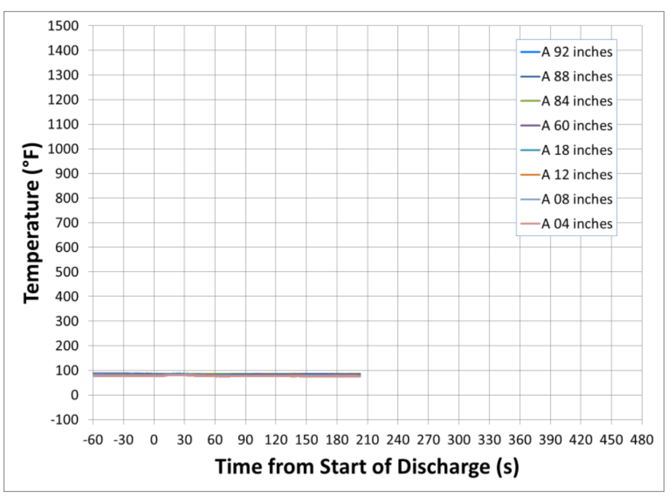
The pressurizer was not used in this experiment. Selected data from this test are shown in Figure 176.



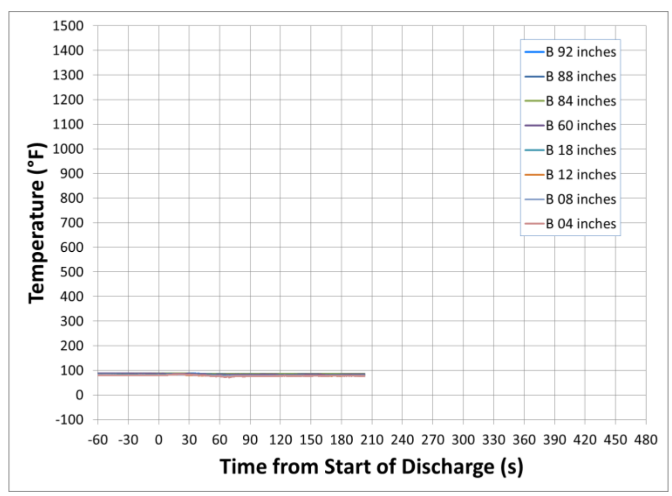
Pressure and Temperature in the Release Tank



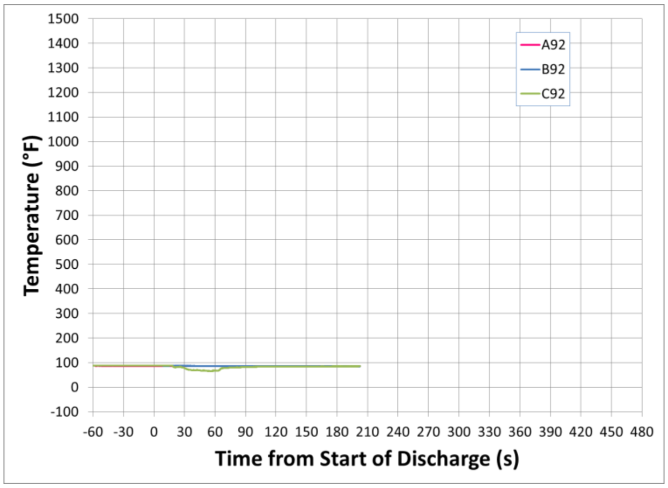
Refrigerant Release Rate



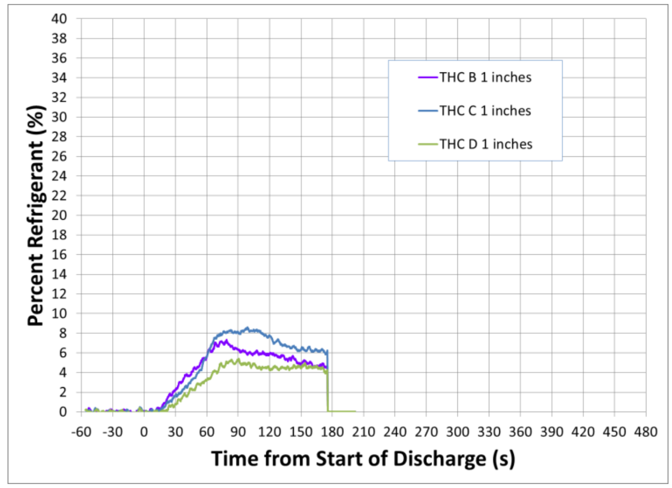
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

View of Location A at 71 seconds after the start of discharge. The flaming lasted for 2 seconds followed by extinguishment of the candle.

Short duration flame (1 second) at 73 seconds after the start of discharge. The candles at Location A, B, and C had been extinguished. The candle at Location D remained lighted throughout the test.

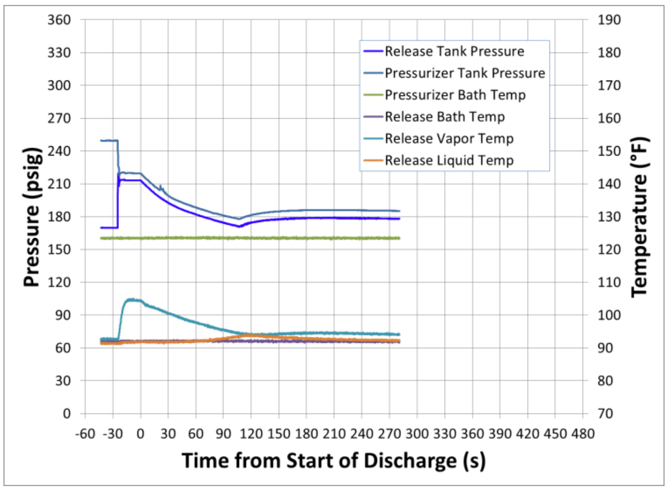
Figure 176 – Data from WALKIN03

WALKIN04:

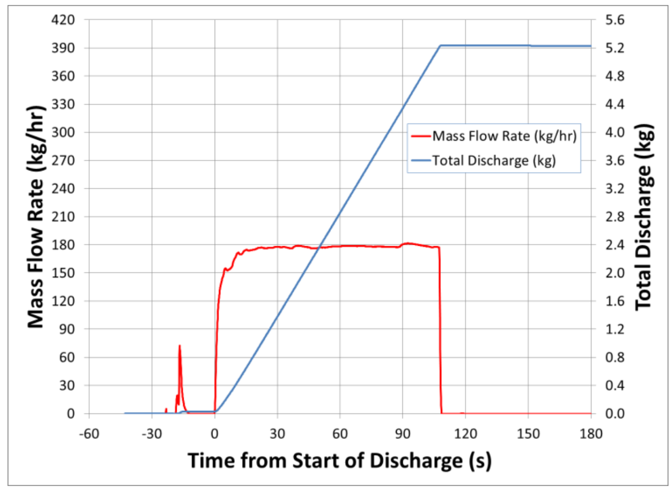
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Actual Discharge (kg)	Door Position	Leak Location	Ignition Result
R-457A	50	4.23	Open	Return Bend	Ignition

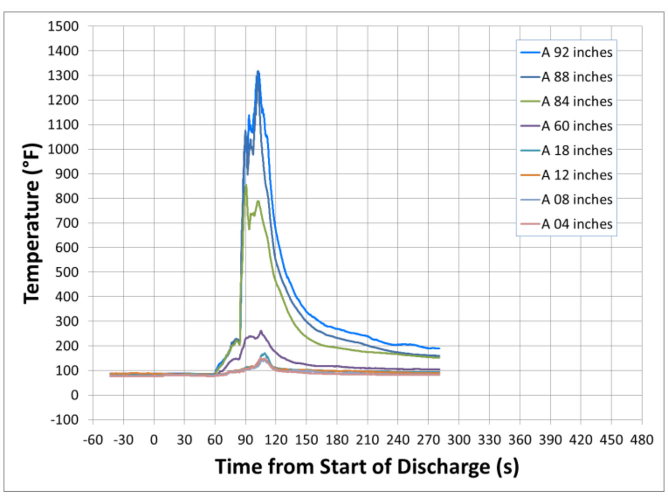
Both the pressurizer and release tanks were used in this experiment. Selected data from this test are shown in Figure 177.



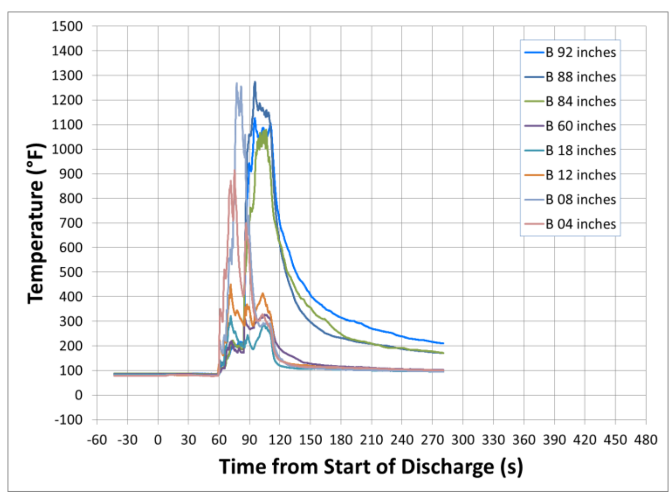
Pressure and Temperature in the Pressurizer and Release Tanks



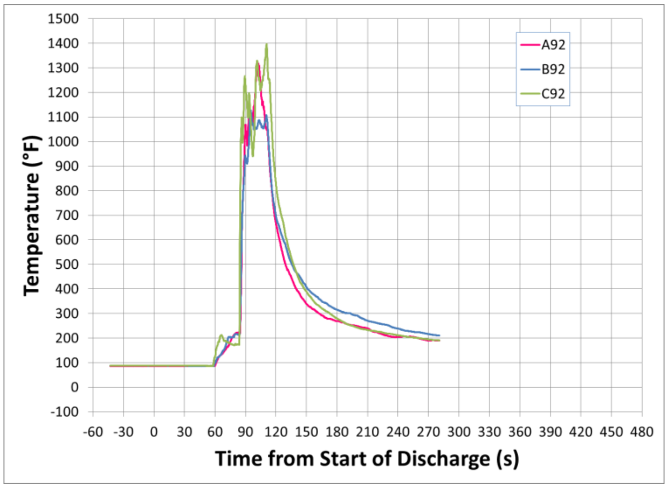
Refrigerant Release Rate



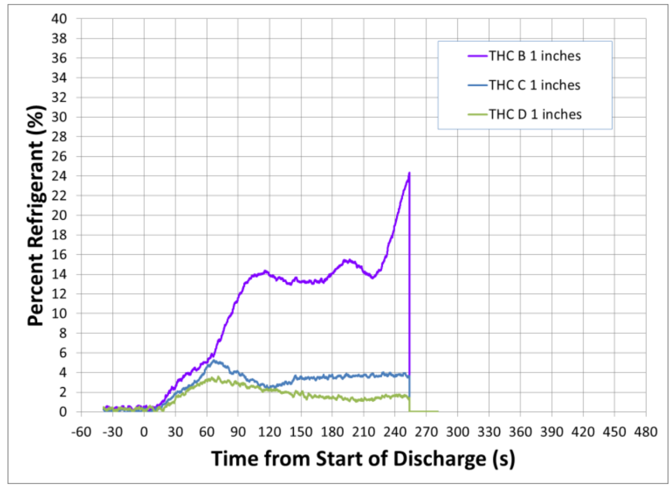
Temperature at Location A



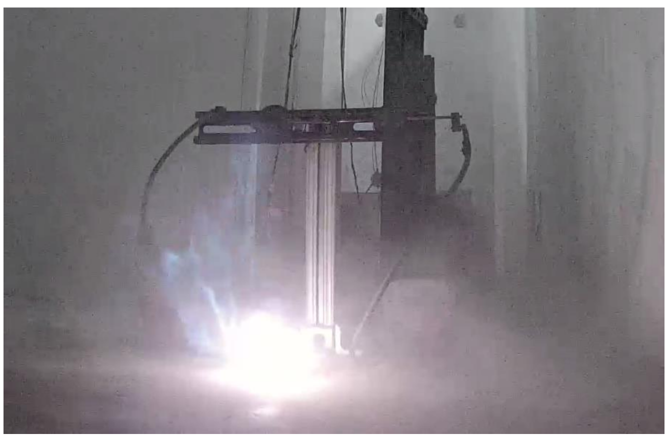
Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration



Ignition at floor level 56 seconds after the start of the discharge.

It appears that liquid refrigerant is dripping from the drain at 63 seconds after the start of the discharge.

<table>
<tr>
<td>
Up until 83 seconds, the fire was at the floor level. This frame shows embers from the cheesecloth floating up to the level of the unit cooler. This caused ignition at the ceiling level.</td>
<td>

At 85 seconds, the volume around the unit cooler was fully involved in flame and the peak pressure was recorded. This frame shows the peak pressure pushing a plume of smoke out of the walk-in cooler and toward the camera. The total duration of flaming was 58 seconds.</td>
</tr>
</table>

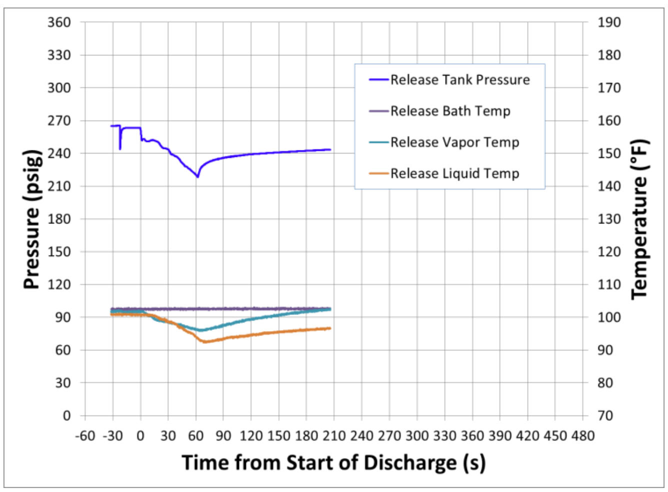
Figure 177 – Data from WALKIN04

WALKIN05:

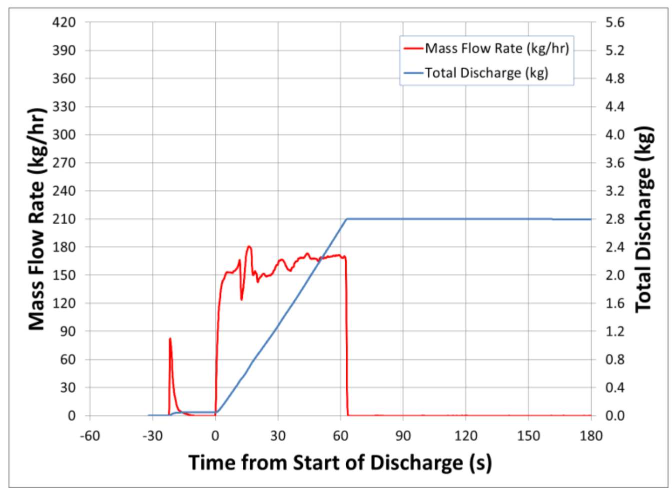
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Actual Discharge (kg)	Door Position	Leak Location	Ignition Result
R-455A	50	2.80	Closed	Coil Face	No Ignition

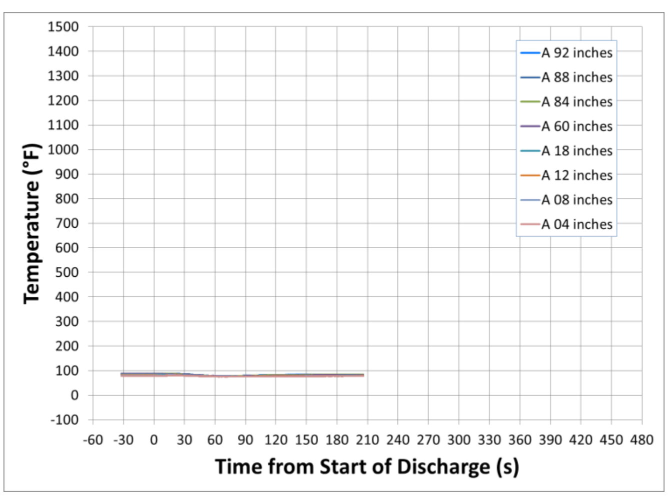
The pressurizer was not used in this experiment. No ignition was observed. It was noted that the candles remained lighted, but were flickering due to the increased air circulation during the discharge. Selected data from this test are shown in Figure 178.



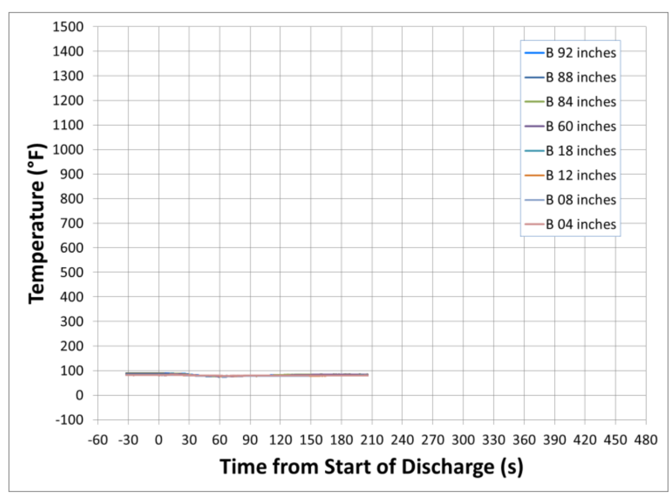
Pressure and Temperature in the Release Tank



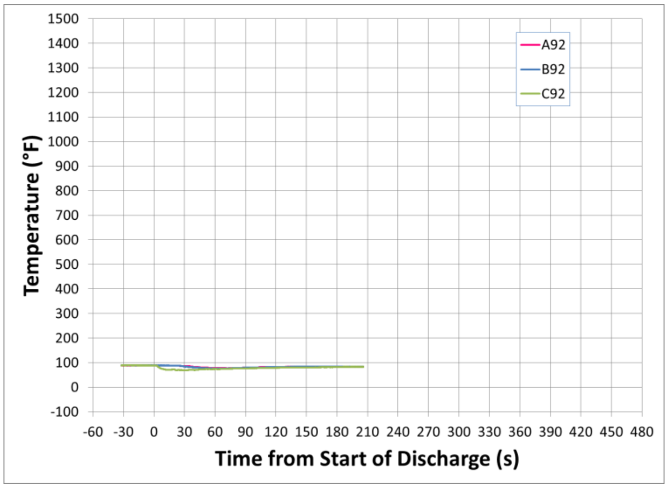
Refrigerant Release Rate



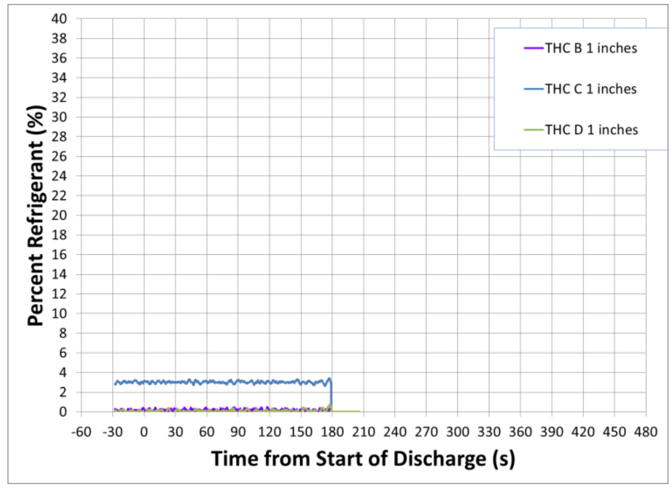
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

The refrigerant lines had become clogged after the previous experiment. The constant values shown in the graph are due to residual concentrations trapped in the sensors and do not represent the experimental data.

The discharge in the coil face caused the fan to rotate. Note the frost buildup on the right-hand fan blades.

After the discharge was completed the fan stopped rotation and the frost began to melt away.

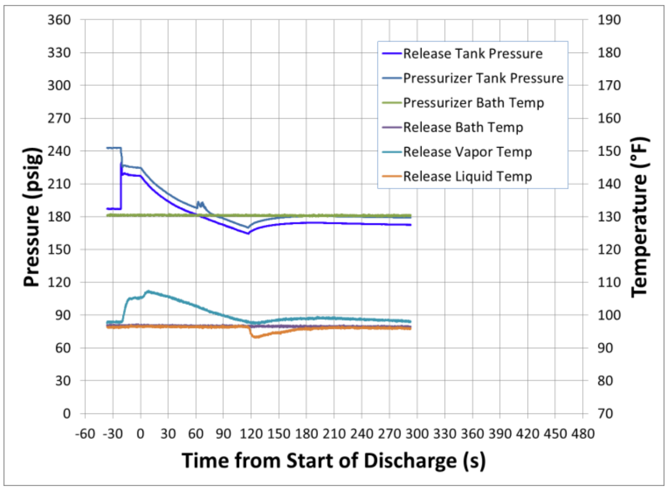
Figure 178 – Data from WALKIN05

WALKIN06:

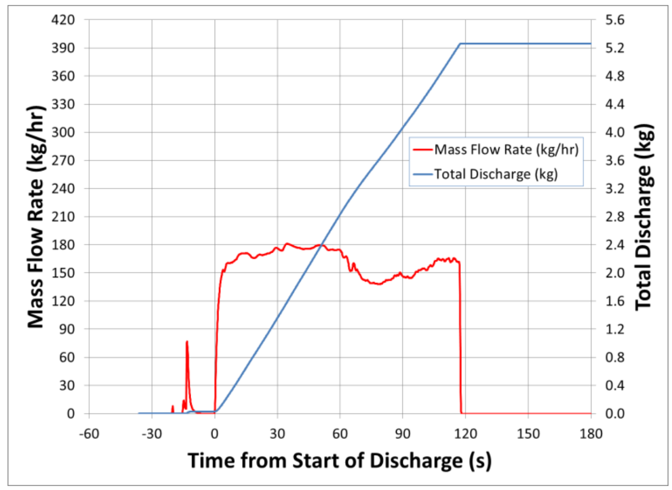
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Actual Discharge (kg)	Door Position	Leak Location	Ignition Result
R-457A	50	5.26	Closed	Coil Face	Ignition

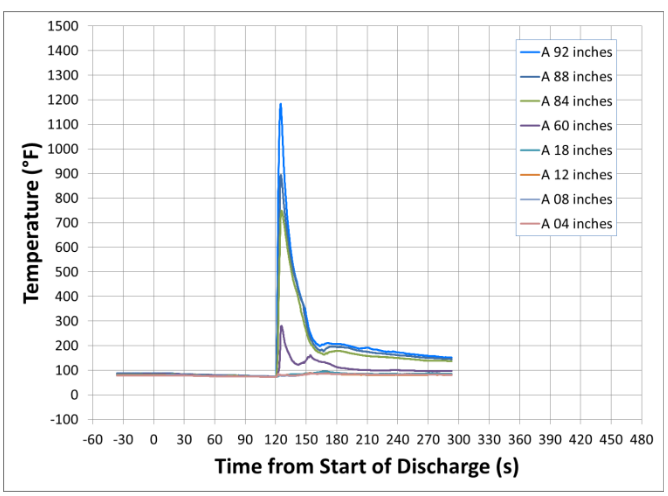
Both the pressurizer and release tanks were used in this experiment. Selected data from this test are shown in Figure 179.



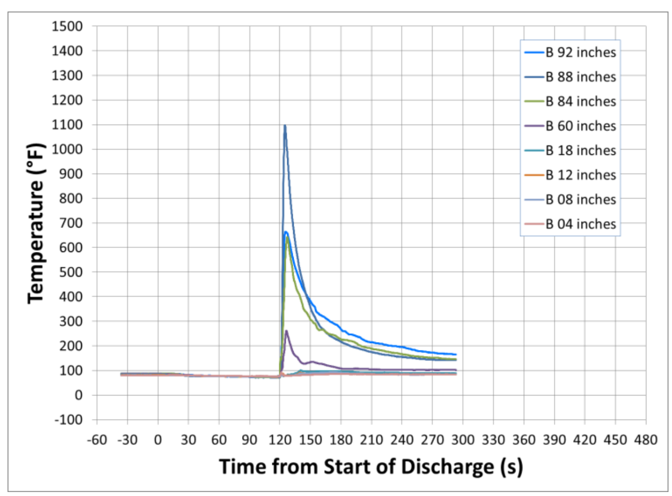
Pressure and Temperature in the Pressurizer and Release Tanks



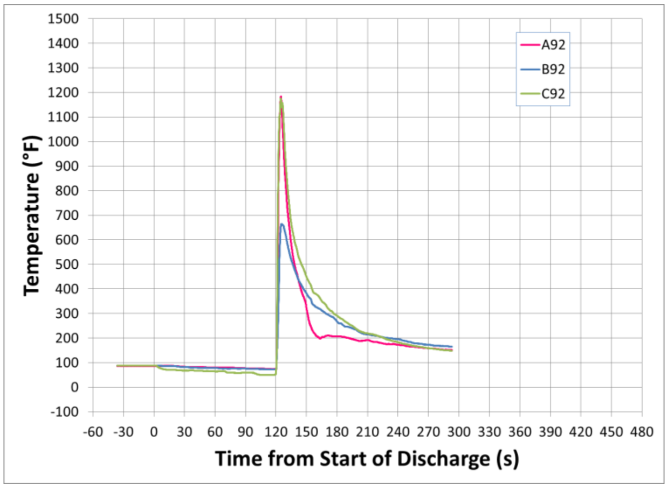
Refrigerant Release Rate



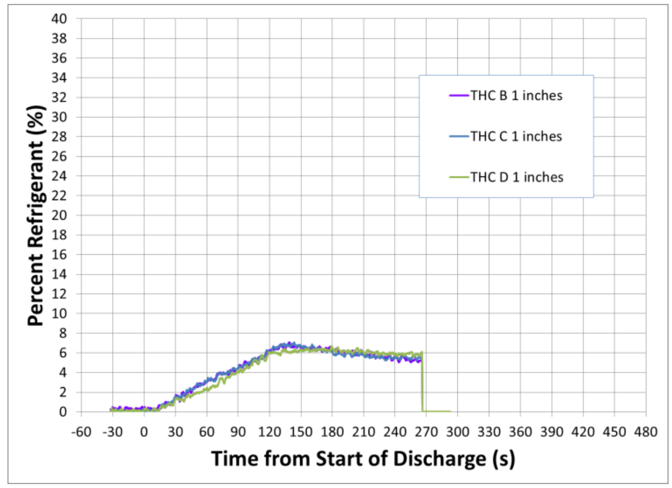
Temperature at Location A



Temperature at Location B



Temperature at 92 in. height above the floor



Refrigerant Concentration

Sustained Ignition at floor level 59 seconds after the start of the discharge. Blue flames were seen to ignite and extinguish for three seconds prior to this frame.

One second after the start of sustained ignition, the flames reached the ceiling of the walk-in. The total duration of sustained flaming was 9 seconds.

At 61 seconds after the start of discharge, the walk-in door was forced open due to pressure from the ignition.

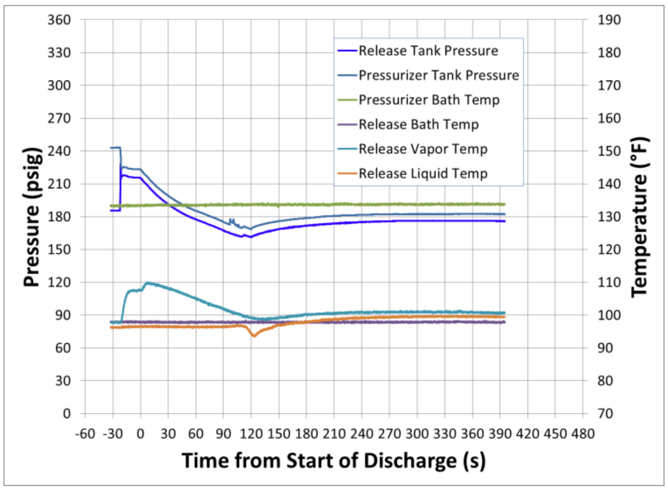
Figure 179 – Data from WALKIN06

WALKIN07:

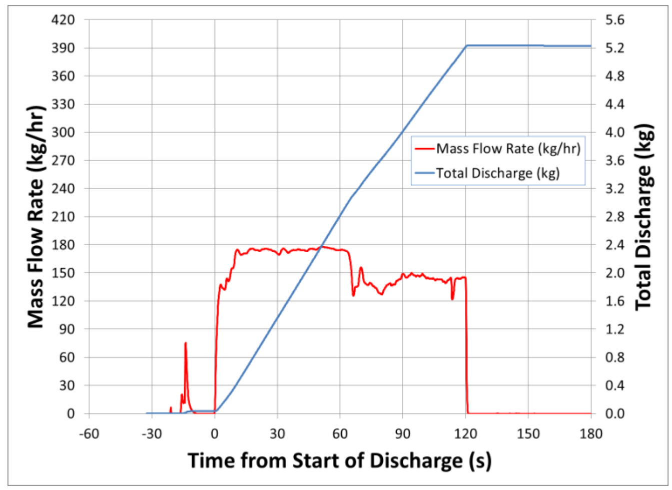
The test parameters for this test were as follows:

Refrigerant	Release rate (g/s)	Actual Discharge (kg)	Door Position	Leak Location	Ignition Result
R-457A	50	5.23	Open	Coil Face	No Ignition

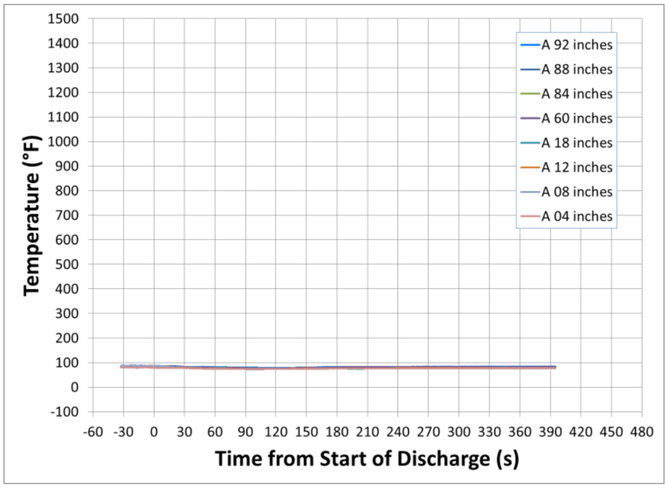
Both the pressurizer and release tanks were used in this experiment. Selected data from this test are shown in Figure 180.



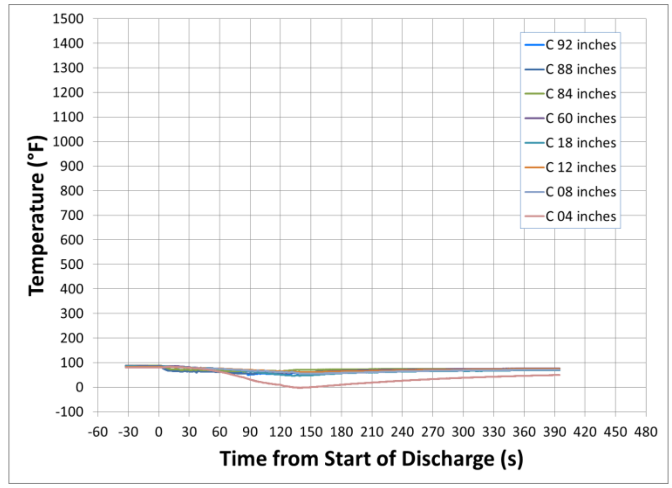
Pressure and Temperature in the Pressurizer and Release Tanks



Refrigerant Release Rate

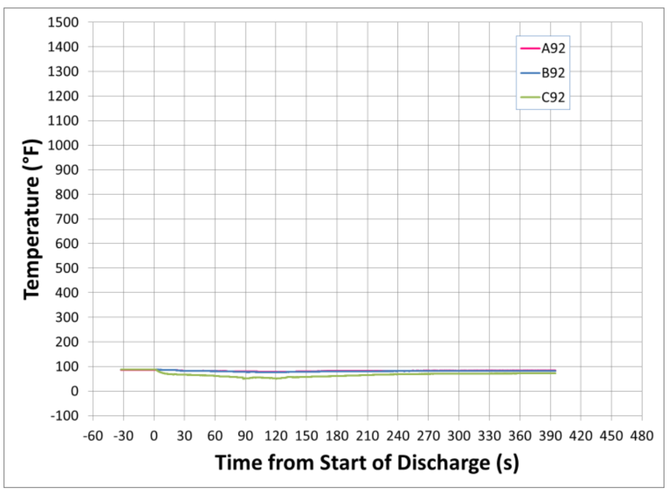


Temperature at Location A

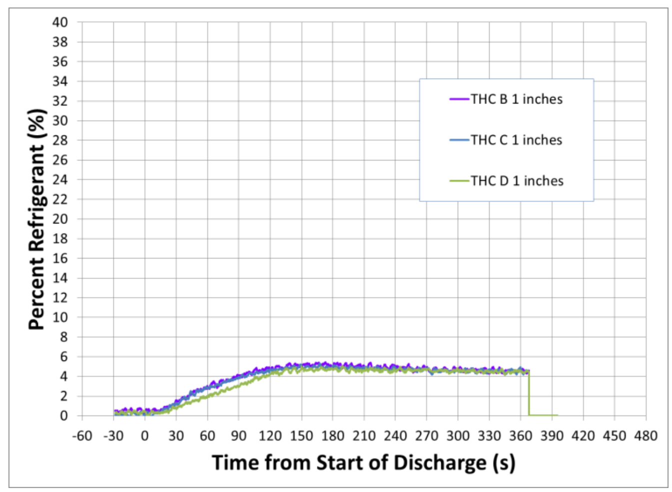


Temperature at Location C

The thermocouple at this location recorded temperatures near 0°F.



Temperature at 92 in. height above the floor



Refrigerant Concentration

There was no ignition during this test. The candles at all locations flickered due to both wind and the presence of refrigerant. Candles at location A, B, and C remained lighted throughout the test. The candle at location D (shown here) was extinguished at 92 seconds after the start of discharge and 27 seconds before the end of the discharge.

Figure 180 – Data from WALKIN07

Appendix F Refrigerant Sensor Calibrations

Refrigerant sensors were calibrated for each refrigerant used in the project. Additional calibrations were completed at any time there was a change in the sample flow configuration that resulted in either a different delay time or signal conversion parameters. Table 49 shows all of the calibrations. The data is sorted by Refrigerant, Date, and Sensor identification. Toward the end of the program, sensor THCn23 had failed and was not used or calibrated after the failure. Gaps in the table are inserted to visually separate one refrigerant from the next.

The real-time refrigerant concentration was based on the following equation:

$$y = mx + b$$

Where:

y is the resulting volume percent of refrigerant concentration (%)
m is the slope of the calibration in percent per millivolt (%/mV)
x is the recorded sensor signal in millivolts (mV)
b is the offset or intercept of the calibration in percent (%)

The parameters response time constant (τ) and Transport Time were also determined during the sensor calibrations and represent the exponential sensor response time and the transport delay time, respectively (in seconds).

Table 49 – Refrigerant Calibration Parameters

Sensor	Refrigerant	Date	m (%/mV)	b (%)	τ (s)	Transport Time (s)
THCn23	R-22	2016-09-16	-699.8	10.0	54.6	11
THCn24		2016-09-16	-698.1	15.4	52.7	11
THCn25		2016-09-16	-666.6	4.1	52.1	11
THCn26		2016-09-16	-644.5	12.0	50.9	11
THCn23		2016-10-23	-697.4	9.7	58.1	20
THCn24		2016-10-23	-696.6	14.7	56.6	20
THCn25		2016-10-23	-668.6	3.7	56.2	20
THCn26		2016-10-23	-643.2	11.6	55.3	20

Sensor	Refrigerant	Date	m (%/mV)	b (%)	τ (s)	Transport Time (s)
THCn23	R-32	2016-08-22	-921.3	13.1	50.6	11
THCn24		2016-08-22	-919.3	20.0	49.1	11
THCn25		2016-08-22	-881.0	5.4	48.3	11
THCn26		2016-08-22	-1111.0	20.6	44.1	11
THCn23		2016-09-16	-921.3	13.1	50.6	11
THCn24		2016-09-16	-919.3	20.0	49.1	11
THCn25		2016-09-16	-874.9	5.5	45.7	11
THCn26		2016-09-16	-852.5	15.8	47.6	11
THCn26		2016-09-16	-852.5	15.8	47.6	11
THCn23		2016-10-27	-921.3	13.1	54.6	20
THCn24		2016-10-27	-919.3	20.0	53.1	20
THCn25		2016-10-27	-881.0	5.4	52.3	20
THCn26		2016-10-27	-852.5	15.8	51.6	20

Sensor	Refrigerant	Date	m (%/mV)	b (%)	τ (s)	Transport Time (s)
THCn23	R-410A	2016-08-22	-1015.3	14.4	51.6	11
THCn24		2016-08-22	-1013.0	22.0	49.5	11
THCn25		2016-08-22	-970.3	5.9	49.0	11
THCn26		2016-08-22	-939.4	17.3	47.9	11
THCn23		2016-09-16	-1015.3	14.4	51.6	11
THCn24		2016-09-16	-1013.0	22.0	49.5	11
THCn25		2016-09-16	-970.3	5.9	49.0	11
THCn26		2016-09-16	-939.4	17.3	47.9	11

Sensor	Refrigerant	Date	m (%/mV)	b (%)	τ (s)	Transport Time (s)
THCn23	R-452B	2016-08-22	-979.4	13.9	56.2	11
THCn24		2016-08-22	-977.2	21.3	55.5	11
THCn25		2016-08-22	-936.4	5.8	53.1	11
THCn26		2016-08-22	-906.6	16.8	52.8	11
THCn23		2016-09-16	-979.4	13.9	56.2	11
THCn24		2016-09-16	-977.2	21.3	55.5	11
THCn25		2016-09-16	-936.4	5.8	53.1	11
THCn26		2016-09-16	-906.6	16.8	52.8	11
THCn23		2016-10-27	-979.4	13.9	60.2	20
THCn24		2016-10-27	-977.2	21.3	59.5	20
THCn25		2016-10-27	-936.4	5.8	57.1	20
THCn26		2016-10-27	-906.6	16.8	64.2	20

Sensor	Refrigerant	Date	m (%/mV)	b (%)	τ (s)	Transport Time (s)
THCn23	R-455A	2016-11-07	-1098.9	16.3	52.5	20
THCn24		2016-11-07	-1095.7	24.3	50.6	20
THCn25		2016-11-07	-1053.4	6.8	48.1	20
THCn26		2016-11-07	-1020.0	19.5	50.6	20
THCn24		2016-11-13	-1130.7	24.9	47.3	23
THCn25		2016-11-13	-1085.2	6.8	45.0	23
THCn26		2016-11-13	-1050.2	19.7	48.7	23

Sensor	Refrigerant	Date	m (%/mV)	b (%)	τ (s)	Transport Time (s)
THCn23	R-457A	2016-11-07	-1071.0	15.8	52.9	20
THCn24		2016-11-07	-1068.0	23.7	51.1	20
THCn25		2016-11-07	-1028.1	6.5	48.4	20
THCn26		2016-11-07	-994.6	18.9	51.3	20
THCn24		2016-11-13	-1069.3	23.7	48.6	23
THCn25		2016-11-13	-1027.7	6.4	46.1	23
THCn26		2016-11-13	-994.5	18.8	50.0	23