Air-Conditioning, Heating and Refrigeration Technology Institute

Final Report

AHRTI Report No. 9013

Experimental Study on the Consequences of Full-scale Ignition Events Involving the A2L Refrigerant R-454C

Final Report

September 2019

By

Scott Davis, Ph.D., P.E. and John Pagliaro, Ph.D., P.E.

Gexcon US

4833 Rugby Avenue, Suite 100

Bethesda, Maryland 20814

Prepared for

AIR-CONDITIONING, HEATING AND REFRIGERATION TECHNOLOGY INSTITUTE, INC

2311 Wilson Boulevard, Suite 400, Arlington, Virginia 22201

AHRTI DISCLAIMER

GEXCON DISCLAIMER

Table of Contents

Executive Summary

In this study, we performed room-scale experiments to evaluate the potential flammability consequences of refrigerant releases from commercial refrigerated display cases (referred to herein as display cases). Tests were designed to compare the potential flammability consequences of display cases when charged with either the A2L refrigerant R-454C or the A3 refrigerant R-290. Because the objective was to study ignition event consequences, we considered certain leak types known to most likely result in flammable concentrations and placed ignition sources in the areas where flammable concentrations would most likely exist, thus forcing relatively low probability, near-worst-case events to occur for the scenarios studied. In addition, certain mitigation measures were evaluated to determine their effectiveness against certain release scenarios.

For a particular display case, the mass of refrigerant will vary based on the density of the refrigerant used as the total internal volume of refrigerant-containing piping and equipment is fixed. Therefore, R-454C charge sizes for the same piece of equipment are approximately twice as large as the “equivalent volume” R-290 charge sizes since R-454C is twice as dense in both the vapor and liquid phases. Furthermore, because of differences in density and vapor pressure, R-454C release rates are approximately 67% higher than R-290 releases rates through the same-sized release orifice. Therefore, to compare the consequences of a particular leak hole size in a particular display case when charged with either R-454C or R-290, different charge sizes and leak rates need to be considered, and that is what was done in this study. R-454C charge sizes varied up to 2000 g and R-290 charge sizes varied up to 1000 g, with the maximum leak rate considered larger than the leak rate of 96% of leaks that are likely to occur (based on the limited available leak frequency data).

In the first series of tests, refrigerants were released into a 287 ft^2 (27 m^2) well-sealed and quiescent test room instrumented with gas sensors to measure refrigerant concentrations at various points in the room. We simulated impinged releases inside display case condensing units as they are most likely to result in higher refrigerant concentrations at the floor capable of exceeded the lower flammability limit (i.e., layered fuel clouds as opposed to uniformly mixed concentrations in the test room). Different release amounts were considered, along with different release positions (top- or bottom-mounted condensing units), and whether the condensing fan was off or on. These tests showed, for the specific environmental conditions provided by the test enclosure, how the refrigerants dispersed in the enclosure and the extent of flammable cloud formation for the various leak characteristics (e.g., leak rates) and equipment characteristics (e.g., charge size and leak position) considered.

During tests with releases inside top-mounted condensing units with the condensing unit fan off, refrigerant concentrations exceeded the lower flammability limit (LFL) in seven out of the twelve tests with R-290 and in none of the equivalent tests with R-454C. During tests with releases inside bottom-mounted condensing units with the condensing unit fan off, refrigerant concentrations exceeded the LFL in all twelve of the tests with R-290 and in seven out of twelve tests with R-454C. The differences are mainly due to the higher LFL for R-454C.

The main observations from the dispersion tests are summarized below:

- The LFL was not reached at any of the concentration sensors during any of the top-mounted condensing unit release tests with R-454C.
- A total of seven tests with R-454C resulted in concentrations above the LFL. All were bottom-mounted condensing unit releases with charges sizes ≥ 600 g and while the condenser fan was off.
- R-454C concentrations were similar to R-290 concentrations when twice the mass of R-454C was released because R-454C vapor is about twice as dense as R-290 vapor.
- Concentrations were slightly higher for the R-454C releases (but still well below the LFL) with the fan on compared to the equivalent R-290 releases because the leak mass flow rates are higher, and the fan speeds were unchanged.

In the second series of tests, we evaluated the ignition consequences of three types of events: (1) impinged releases inside a condensing unit with ignitors energized at the end of the release; (2) releases inside the conditioned space of the display case with the doors closed, followed by one of the doors being opened with ignitors energized in the room; (3) free jet releases with ignition sources in the jet to assess the potential jet fire consequence. Most of the tests were performed in low-humidity air and two tests were repeated in higher-humidity air. During testing, sensors provided the temperature rise at various points in the room, the pressure rise in the room, and the heat flux at various points in the room. Furthermore, video cameras recorded the fire sizes and durations.

The majority of tests with R-454C in low-humidity air either did not ignite or produced small stationary flames anchored to the ignitors that extinguished when the ignitors were turned off. The two R-454C tests that created the largest flames were repeated with higher-humidity air in the test enclosure: one test involved an impinged release in a bottom mounted condensing unit and the other a release inside the conditioned space of the display case. In the higher-humidity test with the release in the condensing unit, the resulting fire was somewhat larger, but still contained within a few-foot radius of the ignitor. When the ignitor was turned off, the fire continued to burn in a pool-fire fashion for about 1.5 minutes. In the in-cabinet R-454C release test with higher-humidity, the fire was larger, more vigorous, and shorter in duration; with the increased reactivity likely due to the flow-induced turbulence created by the refrigerant/air mixture as it exited the display case once the door was opened. The outcome of this test was similar to what was observed in the reach-in cooler tests performed as part of AHRTI 9007. For the R-290 release tests, ignition produced much larger fires that spread across the floor and in some cases throughout the room. With R-290, the fires lasted anywhere from 2 seconds to 5 seconds depending on the amount of R-290 released.

Test results from this study and FPRF-2017-15, “Evaluation of the Fire Hazards of ASHRAE Class A3 Refrigerants in Commercial Refrigeration Applications” enabled ignition consequence comparisons for ten equivalent release scenarios with R-290 and R-454C in dry air. In four of the ten scenarios, the R-290 releases created severe ignition events and R-454C releases resulted in no ignition. In the other six scenarios, the R-290 releases once again created severe ignition events and R-454C releases resulted in small, minimal consequence flames at the ignitors that extinguished when the ignitors were turned off. The two release scenarios repeated with R-454C and the test enclosure pre-conditioned to a higher humidity level resulted in larger, higher consequence flames which were capable of burning remote from a live ignition source. While the ignition events were more severe in humid air, they were still much less severe than the equivalent release scenarios with R-290, whereby the overall fire sizes were still smaller and therefore the heat flux and overpressure hazards were lower.

When releasing “equivalent volume” charge sizes through equivalent leak hole sizes, R-290 ignition events were much more severe for the following reasons: (1) the LFL of R-290 is lower and therefore some of the equivalent releases produced flammable concentrations with R-290 and not with R-454C; and (2) R-290 is much more reactive than R-454C and thus flames could more quickly propagate away from the ignition location to other areas of the room where flammable concentrations existed regardless of the humidity conditions and initial turbulence at the time of ignition. Ignition events involving layered fuel clouds containing R-290 resulted in much larger, short duration fires with much higher heat flux and pressure rise potential. This was not the case for layered fuel clouds containing R-454C, which under low-humidity conditions, could not maintain a flame after the ignitors were turned off. When the reactivity was increased by increasing the humidity in the test enclosure, the resulting fires were still smaller and of longer duration compared to R-290. Only once the reactivity was increased due to higher-humidity and flow-induced turbulence was there a higher consequence ignition event; however, the heat flux and overpressure hazards were still lower compared to R-290 because the overall fire size remained smaller.

The testing showed that for the A2L refrigerant R-454C, the resulting ignition consequences were very minor under quiescent and low humidity conditions, and in fact combustion could only be maintained when the ignition source remained active. Based on these results, it is anticipated that the ignition consequences of other A2L refrigerants with burning velocities below 2 cm/s will also be very minor. In contrast, high consequence events were observed for R-290 under quiescent and low humidity conditions. In order to establish R-454C flames that could propagate away from the ignition source, higher humidity levels were required in order to increase the refrigerants reactivity (i.e., the burning velocity approached 5 cm/s). Higher consequence events did not occur with R-454C until both the humidity was increased (increase in the A2L’s reactivity) and flow induced turbulence was provided to increase the flame speed, resulting in more vigorously burning flames. However, when releasing 1800 g of R-454C under high-humidity and turbulent conditions, the fire size and radiative heat flux were similar to when releasing 150 g of R-290 at 120 g/min below the display case, which was our highest consequence event for R-290 utilizing the current charge limit in UL 60335-2-89 for commercial refrigeration applications.

This study also showed that equivalent releases of R-454C are less likely to result in ignition events altogether because the flammability range is narrower and therefore the flammable layer is typically narrower than during equivalent releases with R-290. With R-454C, it is therefore less likely that an ignition source would be present in the flammable layer because the layer is smaller.

Another potentially hazardous consequence of R-454C ignition events, and all ignition events with fluorinated compounds (i.e., most Class 2 and 2L refrigerants), is the formation of highly toxic combustion products including hydrogen fluoride (HF). Note, even non-flammable fluorinated Class A refrigerants can produce HF when intentionally combusted. While this study did not quantify the levels of hydrogen fluoride in the test room during and after ignition events, qualitative measurements were made within the test room with a 0-10 ppm sensor. For the minor ignition events, HF levels never exceeded 3 ppm and went off range (> 10 ppm) during the higher-consequence tests with high humidity and turbulence. Quantifying HF levels should be a topic of future work to further understand the consequences of ignition events involving fluorinated refrigerants.

1 Introduction

The Heating, Ventilation, Air-Conditioning, and Refrigeration (HVAC&R) industry is transitioning to refrigerant working fluids with lower global warming potential (GWP). A recent study by the National Institute of Standards and Technology [1] examined a comprehensive chemical database and found that most feasible low-GWP working fluids are either flammable or mildly flammable. Furthermore, the study suggested it is highly unlikely that any better-performing fluids will be found. Hence, the use of flammable refrigerants will likely increase in order to reduce the global warming impact of HVAC&R applications.

ANSI/ASHRAE Standard 34 establishes a uniform system for assigning safety classifications to refrigerants. Flammable refrigerants are classified as either 3, 2, or 2L depending on their lower flammability limit, heat of combustion, and maximum burning velocity. While these safety classification “levels” exist, it is not fully clear how the consequences of actual accidental release and ignition events differ for the different classes, with one of the biggest unknowns being the consequences of events involving A2Ls.

The present study evaluates the ignition consequences of the A2L refrigerant R-454C when released from display cases and compares the consequences to the those of similar A3 events. The specific objectives are to: (1) evaluate how the A2L refrigerant R-454C disperses within a room under various release conditions; (2) evaluate the post-ignition consequences of R-454C releases; and (3) compare the ignition consequences to similar tests performed with the A3 refrigerant R-290.

Releases from display cases are replicated in a room-scale test enclosure first without and then with ignition sources present. Refrigerant concentrations throughout the room are measured during the releases and temperature, pressure, and heat flux are measured during the ignition tests, which are also video recorded, to quantify ignition consequences. The test conditions are similar to those considered during tests during R-290 tests in a recent study [2] sponsored by the Fire Protection Research Foundation (FPRF).

2 Background

Gexcon recently performed dispersion and ignition tests with R-290 as part of an FPRF project titled, “Evaluation of the Fire Hazard of ASHRAE Class A3 Refrigerants in Commercial Refrigeration Applications” [2], and in the present report, we refer to these tests as the “FPRF R-290 tests”. As part of that project, we provided a detailed overview of the factors that affect how a refrigerant disperses within a room during a leak, including properties of the refrigerant, characteristics of the leak, properties of the equipment, and aspects of the environment. We then designed tests with feasible release conditions that were most likely to result in flammable concentrations within the test enclosure so that we could explore near-worst-case ignition event consequences.

More specifically, we created low-momentum releases that were representative of leaks within a condensing unit that immediately impinge on a surface (discussed further below). These types of releases are plausible given most display case condensing units are enclosed and contain numerous refrigerant-containing components that are closely packed together. Although it is also plausible to have releases in condensing units that do not impinge on a surface or impinge farther away from the release point, these scenarios were not considered during testing as they are less likely to result in flammable concentrations in the test room [2, 3].

During the FPRF R-290 tests, we evaluated how the refrigerant dispersed within the test room when released above and below a display case to show the potential differences between having a top-mounted or bottom-mounted condensing unit. We also evaluated how R-290 would disperse in the room when the condenser fan was off and on.

After measuring concentrations throughout the test room during forty-eight (48) R-290 releases, we repeated some of the releases with ignitors near the floor energized shortly after the releases ended. In other tests, R-290 was released inside the closed display case and one of the doors was opened with spark ignitors already energized near the floor in front of the unit. Heat flux gauges, pressure transducers, and thermocouples provided the transient heat flux, pressure rise, and temperature rise within the enclosure during the ignition events, and standard- and high-speed cameras provided video footage.

In the present study, dispersion and ignition tests are performed with the A2L refrigerant R-454C and additional tests are performed with the A3 refrigerant R-290 for comparison purposes. R-454C is a blend of 21.5% R-32 and 78.5% R-1234yf by weight and R-290 is refrigerant-grade propane. Table 2.1 provides relevant properties for each refrigerant.

Table 2.1: Refrigerant details.

ASHRAE Number	**R-454C**	**R-290**
Composition (Weight %)	R-32/R-1234yf 21.5/78.5	Propane
Molecular Weight	90.8 g/mol	44.1 g/mol
GWP	< 150	3
Boiling Point @ 1 atm (101.3 kPa)	-45.9 °C (-50.6 °F)	-42.1 °C (-43.8 °F)
Liquid Density @ 21.1 °C	999.5 kg/m^3 (62.4 lb/ft^3)	498.4 kg/m^3 (31.1 lb/ft^3)
Saturated Vapor Density @ 21.1 °C	39.6 kg/m^3 (2.47 lb/ft^3)	18.6 kg/m^3 (1.16 lb/ft^3)
ASHRAE Safety Classification	A2L	A3
LFL (Vol %)	7.7	2.0
LFL	0.293 kg/m^3 (18.3x10^{-3} lb/ft^3)	0.038 kg/m^3 (2.37x10^{-3} lb/ft^3)
UFL (Vol %)	15.5	9.5
UFL	0.585 kg/m^3 (36.5x10^{-3} lb/ft^3)	0.174 kg/m^3 (10.8x10^{-3} lb/ft^3)
Stoichiometric concentration (Vol %)	9.8	4.0
Maximum Burning Velocity @ 23 °C in dry air	1.6 cm/s (0.6 in/s) [4]	40 cm/s (15.7 in/s) [5]
Maximum Burning Velocity @ 27 °C, 100% RH	~ 5 cm/s (2 in/s)[1]	40 cm/s (15.7 in/s)[2]

The A2L refrigerant R-454C was selected for this study because the strictest regulations (e.g., F-Gas) require refrigerants with GWPs of less than 150 for self-contained appliances, like the display case considered in this study and previously in the FPRF R-290 study. Thus, low GWP refrigerants like R-454C are likely to be the only options that will be accepted globally in these types of applications. Note that most if not all of the HFC/HFO refrigerant blends with a GWP less than 150 contain R-32 and R-1234yf and therefore the flammability characteristics of R-454C will generally be representative of the blends that fall within this group.

For hydrofluorocarbon compounds with more fluorine atoms than hydrogen atoms, such as the major constituent of R-454C, R-1234yf ($C_3H_2F_4$), the reactivity is sensitive to the amount of water vapor in the oxidizer (i.e., the amount of humidity in the air). This is because the water vapor in the air reacts with the extra fluorine, which increases the heat release and concentrations of chain-branching radical species in the flame, and thus increases the reactivity. This is not the case for the other constituent of R-454C, R-32 (CH_2F_2), as there are equal amounts of fluorine and hydrogen in the fuel molecule and therefore water in the oxidizer does not increase the heat release or reactivity.

The influence of humidity on reactivity and burning velocity was demonstrated in the JSRAE report [6] for both R-1234yf and R-32 (see Figure 2.1). The measured burning velocity of R-1234yf ($C_3H_2F_4$) increased from roughly 2 cm/s to 10 cm/s as the absolute humidity increased from 0 to 0.07 g-H_2O / g-dry-air when tested at

[1] Unpublished experimental result recently obtained by Gexcon as part of the ASHRAE 1806 project that is still underway.
[2] Propane/air maximum burning velocity is insensitive to humidity and therefore the maximum burning velocity in dry air is referenced.

140 °F (60 °C). The measured burning velocity of R-32 (CH_2F_2) decreased from roughly 8 cm/s to 6 cm/s as the absolute humidity increased from 0 to 0.06 g-H2O / g-dry-air when tested at 140 °F (60 °C).

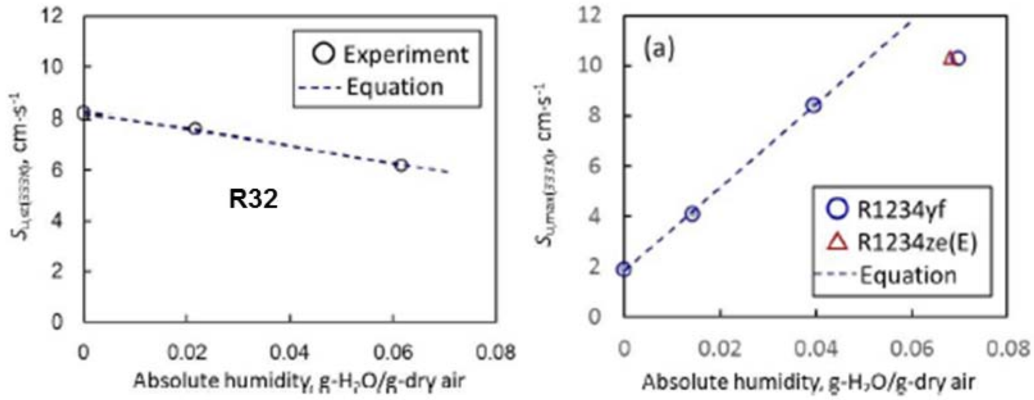


Figure 2.1: Laminar burning velocity as a function of absolute humidity for R32 (left) and R1234yf (right) when tested in air at 140 °F. Figure and data from ref. [6].

In summary, the characteristic of increased reactivity in the presence of water vapor in the oxidizer is unique to hydrofluorocarbon molecules with more fluorine than hydrogen. Furthermore, water vapor in the oxidizer does not increase the reactivity of hydrocarbon refrigerants, including R-290 propane, as the combustion chemistry is completely different.

3 Test Enclosure

Gexcon built a new test enclosure because the one used during the FPRF R-290 tests was partially damaged and additional features were needed to safely run tests with fluorinated refrigerants. The new enclosure is similar in size and shape to the enclosure used during the FPRF R-290 tests, but with stainless steel interior surfaces so that it can be easily cleaned after ignition tests. The new enclosure has five rectangular “vent” openings (see Figure 3.1 and Figure 3.2) near the ceiling for installing pressure relief panels to prevent structural damage during ignition tests. Three of the vents are 49.5 cm tall and 132 cm wide, one is 49.5 cm tall and 126 cm wide, and one is 49.5 cm tall and 121 cm wide. In the present tests the vent openings were covered with plastic film with a yield pressure of approximately 0.3 psig. Table 3.1 provides the dimensions of the new test enclosure, previous test enclosure using in the FPRF R-290 tests, and display case inside the enclosure. The same four-door display case from the FPRF R-290 tests was used in the present study. As discussed in more detail below, a few R-290 dispersion and ignition tests that were performed in the old enclosure were repeated in the new enclosure and the results were similar.

Table 3.1: Dimensions of the new test enclosure, previous test enclosure used during the FPRF R-290 tests, and the display case located in the test enclosure.

Dimensions	New Test Room Interior	Old Test Room Interior	Display Case Exterior
Length	5.8 m (19.0 ft)	5.9 m (19.4 ft)	2.5 m (8.2 ft)
Width	4.6 m (15.1 ft)	4.7 m (15.4 ft)	0.95 m (3.1 ft)
Height	2.4 m (7.9 ft)	2.4 m (7.9 ft)	2.0 m (6.6 ft)
Floor Area	26.7 m^2 (287 ft^2)	27.7 m^2 (299 ft^2)	1.9 m^2 (20.5 ft^2)
Volume	63.1 m^3 (2228 ft^3)	66.4 m^3 (2347 ft^3)	4.75 m^3 (168 ft^3)

The test enclosure is well-sealed and insulated to reduce convective flows and to minimize air change rates. There is no room ventilation system such as a central heating/AC system and therefore the test enclosure provides an extremely quiescent environment during releases. Typical conditioned spaces where display cases are located, such as convenience stores, restaurants, kitchens, etc. will have higher air change rates and ventilation-induced mixing. Hence, tests in the enclosure will yield the conservatively highest concentrations that could result during low-momentum releases as more mixing with air reduces the likelihood of refrigerant concentrations exceeding the LFL near the floor (so long as the quantity of refrigerant released results in concentrations below 25% LFL when homogeneously mixed in the room).

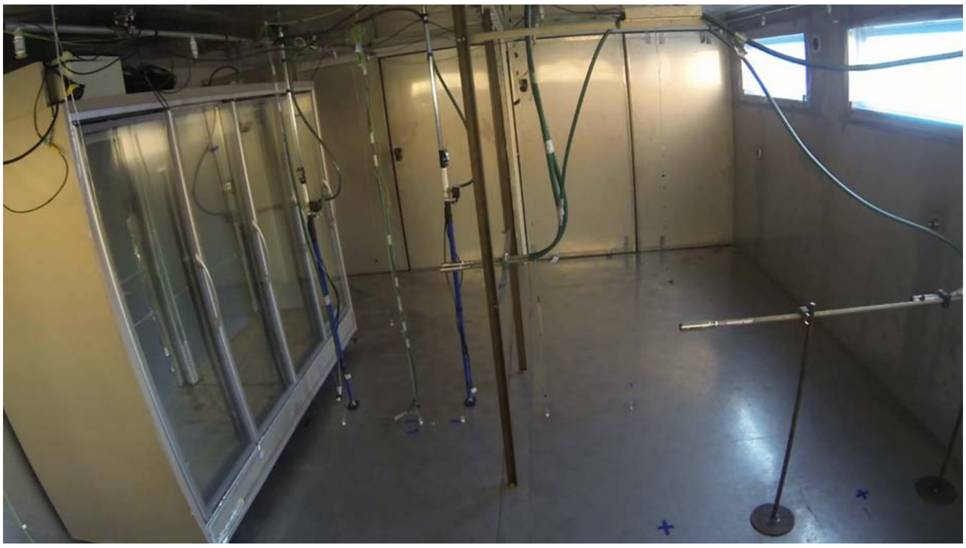


Figure 3.1: Test enclosure view #1.

Figure 3.2: Test enclosure view #2.

4 Dispersion Tests

Refrigerant releases were first performed without ignition sources to evaluate how R-454C vapors disperse within a room under various release conditions. We created low-momentum releases using custom leak boxes (see Figure 4.4 and Figure 4.5 below) to simulate severely impinged releases inside condensing units. The leak boxes were placed either above or below the display case to simulate releases inside a condensing unit when mounted at the top or bottom of a display case.

Table 4.1 shows the different parameters that were varied during the tests with R-454C. All combinations were considered for a total of 48 tests (i.e., four released amounts, two leak positions, three leak rates, and two condenser fan conditions).

Table 4.2 shows the test conditions during the FPRF R-290 tests. Note that some of the charge sizes and all of the leak rates are different in the new tests with R-454C. For both refrigerants, a charge size of 150 g was considered because this is the current charge limit in UL 60335-2-89 for commercial refrigeration applications.

The other three R-454C charge sizes considered were larger than the R-290 charges because one of the objectives of the study was to directly compare the consequences for identical display cases charged with either R-454C or R-290. Since for a particular display case, the internal volume of refrigerant-containing piping and equipment is fixed, the mass of refrigerant will vary based on the density of the refrigerant used. Therefore, R-454C charge sizes are approximately twice as large as the "equivalent volume" R-290 charge sizes (600 g, 1200 g, and 2000 g for R-454C compared to 300 g, 600 g, and 1000 g for R-290) since saturated liquid and vapor R-454C are about twice as dense as saturated liquid and vapor R-290.

Table 4.1: R-454C dispersion test conditions in the present study.

Parameters	Count	R-454C Conditions
Charge size / released mass	4	150 g (0.33 lb), 600 g (1.32 lb), 1200 g (2.65 lb), 2000 g (4.41 lb)
Leak position	2	Top, Bottom
Leak rate (equivalent)	3	20 g/min (0.04 lb/min), 200 g/min (0.44 lb/min), 550 g/min (1.21 lb/min)
Condenser fan operation	2	On, Off

Table 4.2: Previous FPRF R-290 dispersion tests.

Parameters	Count	R-290 Conditions
Charge size / released mass	4	150 g (0.33 lbs), 300 g (0.66 lbs), 600 g (1.32 lbs), 1000 g (2.21 lbs)
Leak position	2	Top, Bottom
Leak rate	3	12 g/min (0.03 lb/min), 120 (0.26 lb/min) , 335 g/min (0.74 lb/min)
Condenser fan operation	2	On, Off

While there is a four-door display case in the test room during all tests, we are effectively evaluating the outcomes of leaks from different size display cases by varying the mass of refrigerant released, and the one display case is there for visual demonstration purposes only. For example, the 600 g R-454C and 300 g R-290 releases show the differences in consequences for the same size display case charged with either refrigerant. Furthermore, the 2000 g R-454C and 1000 g R-290 releases show the differences in consequences for a larger unit charged with either refrigerant. Note that the display case in the test room operates on a 900 g R-290 charge.

Leak rates were also higher during the R-454C tests because the goal was to compare the outcomes of releases from similar hole sizes (see Table 4.3). R-454C has a higher density and vapor pressure and therefore release rates are higher through the same size holes.

The different leak rates in Table 4.3 correspond to pure liquid and vapor releases through different sized orifices. Leak frequency data suggests that 96% of leaks likely to occur will have a diameter smaller than 0.54 mm and 99% will have a diameter smaller than 1.15 mm [2, 7, 8]. This means that at least 96% of actual leaks will have leak rates smaller than the largest leak rate considered in this study (i.e., 335 g/min for R-290 and 550 g/min for R-454C). It is noted that leak frequency data is quite limited, and significant uncertainties exist in the current data.

Note that in all dispersion tests, vapor refrigerant was released. The different leak rates were achieved by varying the release pressure through a fixed-size orifice.

Table 4.3: Equivalent mass flow rates for R-290 and R-454C vapor- and liquid-phase releases through the same hole sizes.

Liquid-phase release at 55 °C (131 °F)		
Leak diameter	R-290 mass flow rate (g/min)	R-454C mass flow rate (g/min)
0.10 mm (0.004 in)	12	20
0.32 mm (0.013 in)	120	200
0.54 mm (0.021 in)	335	550

Vapor-phase release at 55 °C (131 °F)		
Leak diameter	R-290 mass flow rate (g/min)	R-454C mass flow rate (g/min)
0.22 mm (0.009 in)	12	20
0.69 mm (0.027 in)	120	200
1.15 mm (0.045 in)	335	550

4.1 Release details

Vapor compression cycles have high working pressures and therefore refrigerant releases will have high momentum. When there is a high-momentum release into open space (i.e., an un-impinged release), the released fluid rapidly mixes with air due to the high fluid velocity and induced turbulence. This mixing mechanism is often referred to as jet-induced mixing. For example, consider pure refrigerant vapor released into an open space from a failed brazed connection. Pure refrigerant exits at the release point and air is entrained into the release jet downstream of the release point, diluting the released refrigerant and thus the refrigerant concentration continually decreases with distance from the release point as illustrated in Figure 4.1.

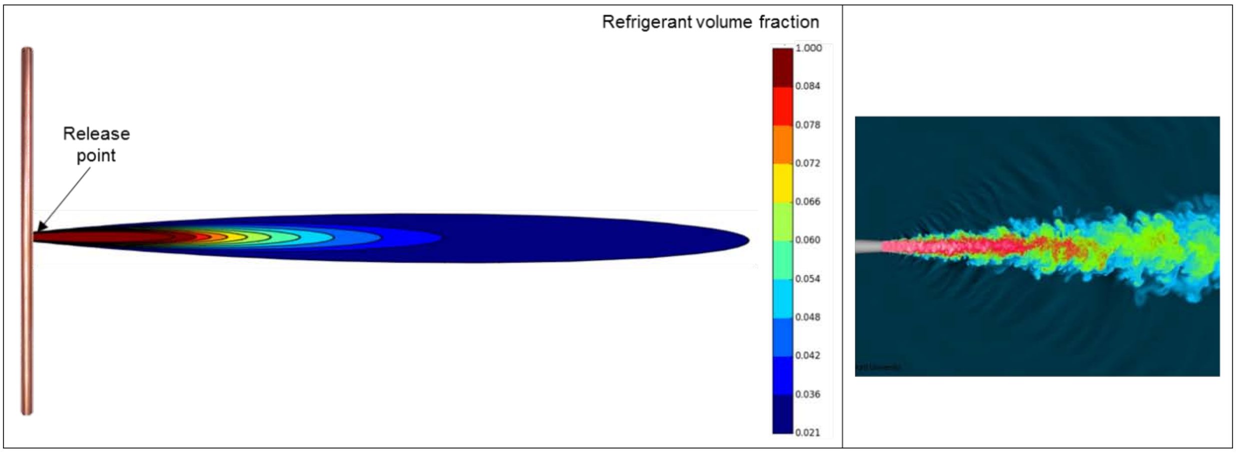


Figure 4.1: Example of the steady-state concentration during an un-impinged vapor jet release of refrigerant from a vapor compressor cycle. Left image shows FLACS simulation and right image shows a direct numerical solution with the turbulent shear layers visible at the fuel/air interface.

When a high-pressure, high-momentum release impinges on a solid surface and/or occurs in a confined area, the amount of jet-induced mixing is reduced. This can have a significant impact on the resulting concentrations in a room during a leak. The degree of reduction in mixing depends on certain factors such as the distance between the release point and the surface onto which the release impinges, along with the confinement characteristics where the release occurs. For example, and as illustrated in Figure 4.2, a release that immediately impinges on a surface will immediately lose momentum (left image) and have less jet-induced mixing compared to a release that impinges on a surface farther away from the release point (right image). The release that impinges closer to the release point will be more likely to result in flammable concentrations at the floor or ceiling if the refrigerant is more or less dense than air, respectively.

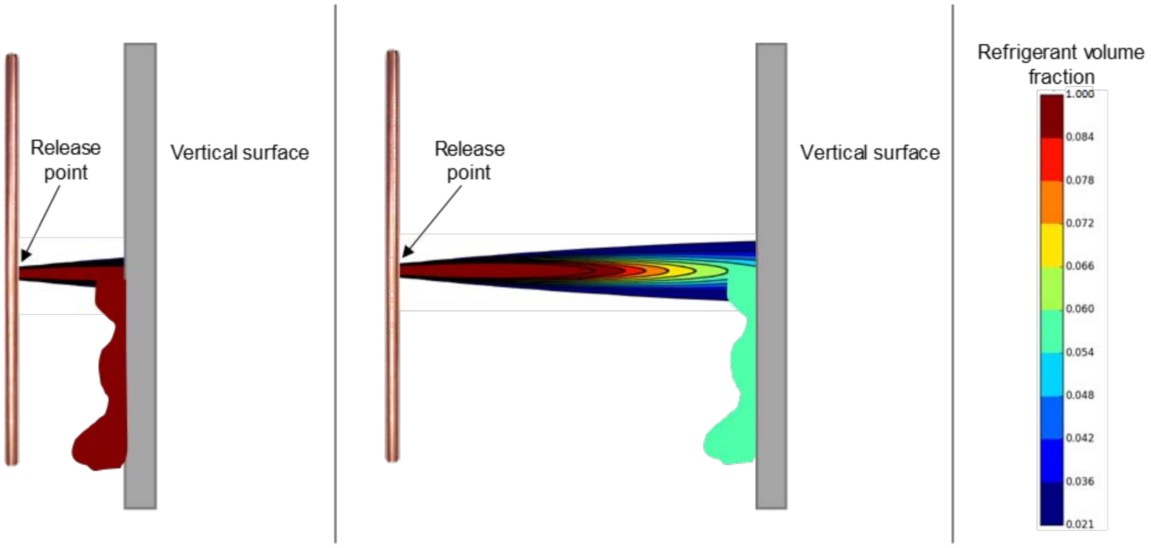


Figure 4.2: Differences in the amount of jet-induced mixing for releases that impinge on a surface at different distances from the release point.

It is important to consider the effects of release impingement/confinement as piping and refrigerant-containing equipment (e.g., the compressor and condenser) are typically enclosed and closely packed together. For example, Figure 4.3 shows the condensing unit on the display case in the test setup.

Figure 4.3: Condensing unit enclosure on the display case used in the test setup.

In the present study, like done in the FPRF R-290 tests, we purposely create highly impinged releases that lose momentum immediately and thus have very little jet-induced mixing. Hence, the outcomes of the releases in terms of flammable cloud formation are considered representative of the highest concentration layer cases since not all releases within a condensing unit will be as highly impinged. To create highly impinged low-momentum releases, refrigerants are released inside the small boxes shown in Figure 4.4. As done in the FPRF R-290 tests, a separate box with different internal volume and outlet area was used for each release mass flow rate considered so that the release velocities were similar in all tests (i.e., for all release rates). Figure 4.5 shows one of the release boxes mounted under the display case before a test.

Figure 4.4: Release boxes used to create highly impinged low-momentum releases.

Figure 4.5: Leak box positioned below the display case.

For release scenarios with the condenser fan on, refrigerants are released inside a mock-up condensing unit enclosure shown in Figure 4.6. The release is pointed upwards inside the enclosure which has a 20.3 cm (8 in) diameter variable-speed fan at one end and is open at the other end. For refrigerated display cases, the condenser fan flow rate is proportional to the amount of heat that needs to be removed from the condenser, which is proportional to the cooling capacity of the unit. Therefore, we used the same fan flow rates that were used in the FPRF R-290 tests (see Table 4.4).

Figure 4.6: Mock-up condensing unit to replicate releases with the condensing fan on.

Table 4.4: Condenser fan flow rate versus R-454C and R-290 charge size.

R-454C Charge Size	R-290 Charge Size	Condenser Fan Flow Rate
150 g (0.33 lbs)	150 g (0.33 lbs)	150 m^3/hr (5297 ft^3/hr)
600 g (1.3 bls)	300 g (0.66 lbs)	300 m^3/hr (10594 ft^3/hr)
1000 g (2.2 lbs)	600 g (1.3 bls)	600 m^3/hr (21188 ft^3/hr)
2000 g (4.4 lbs)	1000 g (2.2 lbs)	1000 m^3/hr (35314 ft^3/hr)

4.2 Instrumentation

Oxygen (O_2) sensors provided the oxygen concentration at various points in the enclosure during refrigerant releases. Assuming air is 20.9 % oxygen, the oxygen concentration measurements indirectly provided the refrigerant concentrations. We used Teledyne R22a oxygen sensors which have a range of 0% to 100% O_2 and a response time of less than 6 seconds when measuring oxygen concentrations between 0% and 90%. We verified in preliminary testing that the sensor response time was as fast as reported. Sensor measurement uncertainty is reported as a linearity of ± 1% of full scale and a temperature compensation of ± 5% of reading over the operating range.

Infrared (IR) sensors were used in the FPRF R-290 tests to directly measure propane concentrations. We did not use these sensors in this project because they may be damaged by the corrosive combustion products formed when R-454C burns. However, during commissioning tests with R-290 releases, measurements were made with Teledyne R22a oxygen sensors and the IR sensors and the two gave very similar propane concentration results.

Thirteen O_2 sensors were positioned in the test room at the locations provided in Figure 4.7. These are the same locations where concentration sensors were placed during the FPRF R-290 tests.

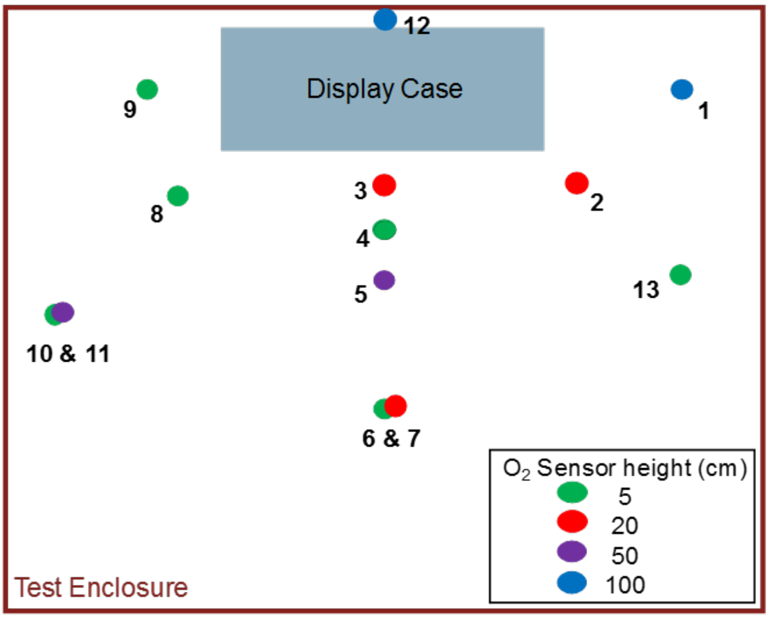


Figure 4.7: Concentration sensors used to determine refrigerant concentration at various points in the room.

4.3 Results

Prior to performing dispersion tests with R-454C, we repeated a few of the FPRF R-290 tests to evaluate the repeatability of the testing and the verify that the small differences in the new and old enclosure had minimal influence on the results. This preliminary testing showed that the tests were very repeatable, and the results were similar to what was measured previous in the old test enclosure.

Table 4.5 and Table 4.6 summarize the conditions for equivalent R-290 and R-454C releases with the condenser fan off and on respectively. The tables indicate which releases resulted in concentrations above the LFL when releasing R-454C in the present study and R-290 in the previous study [2]. As discussed above, direct comparisons of releases from the same display case and through the same hole size require different release amounts and release rates to account for the differences in refrigerant properties, hence the differences for R-290 and R-454C in each row.

For top releases with the fan off, refrigerant concentrations exceeded the LFL in seven out of the twelve tests with R-290 and in none of the equivalent tests with R-454C. For bottom releases with the fan off, refrigerant concentrations exceeded the LFL in all twelve of the tests with R-290 and in seven out of twelve tests with R-454C. For all releases with the fan on (top and bottom), refrigerant concentrations did not exceed the LFL for all 24 cases for R-454C and almost all (23 out of 24 cases) for R-290.

The main observations from the dispersion tests are summarized below:

- The LFL was not reached at any of the concentration sensors during any of the top release tests with R-454C, as compared to R-290 where seven out of twelve tests exceeded the LFL when the fan was off and none exceeded the LFL with the fan on.
- A total of seven tests with R-454C resulted in concentrations above the LFL. All were bottom releases with charges sizes ≥ 600 g and while the condenser fan was off. All twelve bottom releases with the fan off resulted in concentrations that exceeded the LFL for R-290.
- For all releases with the fan on (top and bottom), refrigerant concentrations did not exceed the LFL for all 24 cases for R-454C and almost all (23 out of 24 cases) for R-290
- R-454C concentrations were similar to R-290 concentrations when twice the mass of R-454C was released because R-454C vapor is about twice as dense as R-290 vapor. Meaning one mole or volume of R-454C vapor is twice as dense as one mole or volume of R-290.
- The new test enclosure provided a more quiescent environment and therefore concentrations were slightly higher near the floor during the new tests compared to the previous tests performed during the FPRF R-290 project. In other words, there was less mixing due to natural convection.
- There is no seam in the center of the new enclosure and therefore floor concentrations were more uniform during bottom releases compared to the previous tests.
- Concentrations were slightly higher for the R-454C releases (but still well below the LFL) with the fan on compared to the equivalent R-290 releases because the leak mass flow rates are higher, and the fan speeds were unchanged, and were only correlated to unit capacity.

The raw data of R-454C concentration versus time at each sensor during each R-454C test is provided in Appendix A.

Table 4.5: Dispersion test conditions and results summary for tests with the condenser fan off.

Test #	Release Location	Leak Rate (g/min)		Condenser Fan	Charge Size (g)		Above LFL with	Above LFL with
		R-290	R-454C	(Off/On)	R-290	R-454C	R-290?	R-454C?
1	Top	12	20	Off	150	150	No	No
2	Top	12	20	Off	300	600	No	No
3	Top	12	20	Off	600	1200	No	No
4	Top	12	20	Off	1000	2000	No	No
9	Top	120	200	Off	150	150	No	No
10	Top	120	200	Off	300	600	**Yes**	No
11	Top	120	200	Off	600	1200	**Yes**	No
12	Top	120	200	Off	1000	2000	**Yes**	No
17	Top	335	550	Off	150	150	**Yes**	No
18	Top	335	550	Off	300	600	**Yes**	No
19	Top	335	550	Off	600	1200	**Yes**	No
20	Top	335	550	Off	1000	2000	**Yes**	No
25	Bottom	12	20	Off	150	150	**Yes**	No
26	Bottom	12	20	Off	300	600	**Yes**	No
27	Bottom	12	20	Off	600	1200	**Yes**	**Yes**
28	Bottom	12	20	Off	1000	2000	**Yes**	**Yes**
33	Bottom	120	200	Off	150	150	**Yes**	No
34	Bottom	120	200	Off	300	600	**Yes**	No
35	Bottom	120	200	Off	600	1200	**Yes**	**Yes**
36	Bottom	120	200	Off	1000	2000	**Yes**	**Yes**
41	Bottom	335	550	Off	150	150	**Yes**	No
42	Bottom	335	550	Off	300	600	**Yes**	**Yes**
43	Bottom	335	550	Off	600	1200	**Yes**	**Yes**
44	Bottom	335	550	Off	1000	2000	**Yes**	**Yes**

Table 4.6: Dispersion test conditions and results summary for tests with the condenser fan on.

Test #	Release Location	Leak Rate (g/min)		Condenser Fan (Off/On)	Charge Size (g)		Above LFL with R-290?	Above LFL with R-454C?
		R-290	R-454C		R-290	R-454C		
5	Top	12	20	On	150	150	No	No
6	Top	12	20	On	300	600	No	No
7	Top	12	20	On	600	1200	No	No
8	Top	12	20	On	1000	2000	No	No
13	Top	120	200	On	150	150	No	No
14	Top	120	200	On	300	600	No	No
15	Top	120	200	On	600	1200	No	No
16	Top	120	200	On	1000	2000	No	No
21	Top	335	550	On	150	150	No	No
22	Top	335	550	On	300	600	No	No
23	Top	335	550	On	600	1200	No	No
24	Top	335	550	On	1000	2000	No	No
29	Bottom	12	20	On	150	150	No	No
30	Bottom	12	20	On	300	600	No	No
31	Bottom	12	20	On	600	1200	No	No
32	Bottom	12	20	On	1000	2000	No	No
37	Bottom	120	200	On	150	150	No	No
38	Bottom	120	200	On	300	600	No	No
39	Bottom	120	200	On	600	1200	No	No
40	Bottom	120	200	On	1000	2000	No	No
45	Bottom	335	550	On	150	150	**Yes**	No
46	Bottom	335	550	On	300	600	No	No
47	Bottom	335	550	On	600	1200	No	No
48	Bottom	335	550	On	1000	2000	No	No

5 Ignition Tests

Table 5.1 through Table 5.3 list the ignition tests performed in the present study. The tests are separated into three groups based on the refrigerant release type. The tests in Table 5.1 are repeats of the dispersion tests involving impinged low momentum releases above or below the display case (i.e., simulated releases inside a condensing unit), but with ignitions triggered just after the releases end. Tests in Table 5.2 involved releases inside the conditioned space of the display case while the doors are closed. Refrigerant was released as both a free jet to create uniform mixing in the display case and as an impinged jet using the leak boxes to create a layered rich cloud at the base of the cabinet. After the releases ended, ignitors were turned on in front of the display case and one of the doors was opened. Lastly, tests in Table 5.3 involved free jet releases with an ignitor close to the release point to evaluate the potential severity of turbulent jet flames with R-454C. For these tests, liquid and vapor refrigerant were released to evaluate the consequences of both since refrigerant exists as both a vapor and liquid in a refrigeration cycle.

Prior to performing the tests in Table 5.1 through Table 5.3, we performed commissioning tests and repeated two of the ignition tests from the FPRF R-290 study. The repeat R-290 ignition tests created very similar ignition events to what was observed during the previous study and the commissioning tests ensured that all instrumentation was recording prior to starting the test series. Furthermore, we performed several commissioning tests with R-454C to determine the most optimal ignition source configuration for igniting the resulting layered fuel clouds.

The temperature and humidity in the test enclosure were not controlled during the FPRF R-290 ignition tests. Based on the time of year when the tests were performed, temperatures and absolute humidities ranged from approximately 40-78 °F and 0.0044-0.0115 g-H_2O / g-dry-air (dew point of 36-61 °F).

In the present study, temperature and humidity inside the test enclosure were only controlled during two tests. During the other tests, ambient temperatures ranged from 31-48 °F and the absolute humidity was less than or equal to 0.0063 g-H_2O / g-dry-air (dew point of 45 °F) based on weather data. These are referred to as the tests performed in low-humidity conditions and the actual absolute humidity for each test is given in Table 5.1 through Table 5.3 below.

Since the reactivity of R-454C is sensitive to the amount of water vapor in the air, two of the ignition tests were repeated with the temperature in the test room above ambient and with a target absolute humidity in the test room of 0.0227 g-H_2O / g-dry-air, corresponding to 80.6 °F (27 °C) dew point, to evaluate the potential consequences under humid conditions. Electric heaters were placed in the test enclosure and hot plates were used to boil water inside the enclosure while the humidity levels were monitored at three locations. The actual absolute humidity achieved in each test is provided in Table 5.1 (Test #5) and Table 5.2 (Test # 19).

Table 5.1: Ignition tests with simulated condensing unit releases.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
1	R-454C	Bottom	Impinged jet - vapor	20	1200	Off	0.0045
2	R-454C	Bottom	Impinged jet - vapor	200	600	Off	0.0029
3	R-454C	Bottom	Impinged jet - vapor	200	1200	Off	0.0034
4	R-454C	Bottom	Impinged jet - vapor	200	2000	Off	0.0042
5	R-454C	Bottom	Impinged jet - vapor	200	2000	Off	0.0223
6	R-454C	Bottom	Impinged jet - vapor	200	1200	On	0.0044
7	R-454C	Bottom	Impinged jet - vapor	550	600	Off	0.0039
8	R-454C	Bottom	Impinged jet - vapor	550	1200	Off	0.0033
9	R-454C	Top	Impinged jet - vapor	200	2000	Off	0.0040
10	R-290	Bottom	Impinged jet - vapor	12	300	Off	< 0.0063
11	R-290	Bottom	Impinged jet - vapor	335	300	Off	< 0.0063
12	R-290	Bottom	Impinged jet - vapor	335	600	Off	< 0.0063
13	R-290	Bottom	Impinged jet - vapor	120	600	Off	< 0.0063
14	R-290	Top	Impinged jet - vapor	120	600	Off	< 0.0063

Table 5.2: Ignition tests with releases inside the display case conditioned space.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
15	R-454C	Inside	Free jet - vapor	200	900	Off	0.0040
16	R-454C	Inside	Impinged jet - vapor	200	900	Off	0.0055
17	R-454C	Inside	Free jet - vapor	200	1800	Off	0.0042
18	R-454C	Inside	Impinged jet - vapor	200	1800	Off	0.0045
19	R-454C	Inside	Free jet - vapor	200	1800	Off	0.0236
20	R-290	Inside	Impinged jet - vapor	120	900	Off	< 0.0063
21	R-290	Inside	Free jet - vapor	120	900	Off	< 0.0063

Table 5.3: Ignition tests with free jet releases to evaluate jet flame severity.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
22	R-454C	In front	Free jet - vapor	550	1000	Off	< 0.0063
23	R-454C	In front	Free jet - liquid	4450	1000	Off	< 0.0063

5.1 Ignition test setup and instrumentation

Heat flux was measured at four locations in the test room (see Figure 5.1) using Vatell Corporation heat flux sensors (model number TG1000-1 coupled with a signal amplifier). Two of the gauges had a range of 0-50 kW/m^2 and a response time of 1 s. These were the gauges used in the FPRF R-290 tests. The other two gauges were new and had a range of 0-1000 kW/m^2 and a much faster response time of 20 ms. Two sensors were placed very close to each other, one with a range of 0-50 kW/m^2 and a response time of 1 s and the other with a range of 0-1000 kW/m^2 and response time of 20 ms so that the results of the two sensors could be compared. Sensor #3 shown in Figure 5.1 had a range of 0-50 kW/m^2 and sensor #4 had a range of 0-1000 kW/m^2.

The pressure rise during ignition events was recorded inside the room using a pressure transducer. During all tests, the five vent openings were covered with plastic sheets to allow venting during the ignition events, hence the pressure rise in the enclosure was limited during all tests as discussed below in the results section. Temperature was measured at four locations in the room and at three heights at each location, for a total of 12 measurement locations. Several video cameras are mounted in the enclosure to film the ignition events from different angles.

Two O_2 sensors were positioned in front of the display case to provide refrigerant concentrations during the releases and up to a few seconds before ignition. During the tests with R-290, the two sensors were positioned at location 3 and 4 shown in Figure 4.7. During the tests with R-454C, the sensor at position 3 was moved down to 5 cm above the ground and the sensor at position 4 was moved away from the display case to better characterize the refrigerant concentrations near the ignitors. Figure 5.1 shows the locations of the heat flux gauges, pressure transducer, thermocouples, and the O_2 sensors.

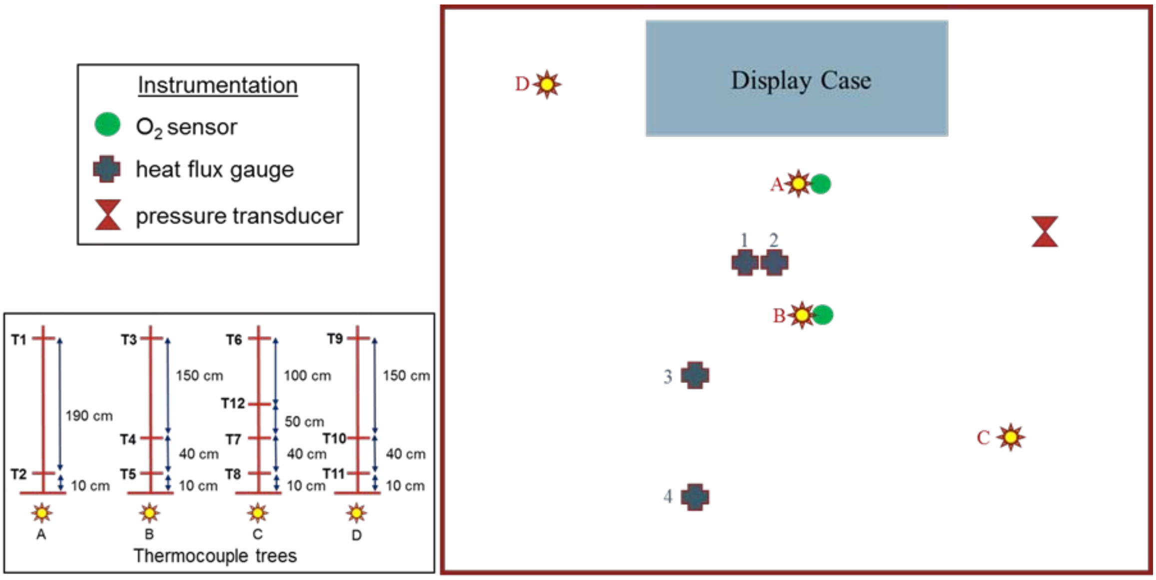


Figure 5.1: Instrumentation locations during the ignition tests.

In the ignition tests, oscillating spark transformers were used as ignition sources. The transformers were Danfoss Type EBI4 with an output voltage of 15 kV and amperage of 40 mA. Each ignition transformer was connected to a pair of electrodes with a large spark gap of 6 mm to minimize flame quenching during tests with R-454C.

We performed preliminary testing to verify the ignitors were strong enough (i.e., had a high enough ignition energy) to ignite R-454C/air mixtures. Premixed R-454C/air mixtures with R-454C concentrations of 8%, 10%, 12%, and 14% were prepared in a small closed chamber with windows and ignition was attempted with the Danfoss transformers with electrodes spaced 6 mm apart. Ignition occurred in each test confirming that these ignitors could ignite premixed R-454C/air mixtures over a wide range of equivalence ratios (reported LFL = 7.7% and UFL = 15.5%).

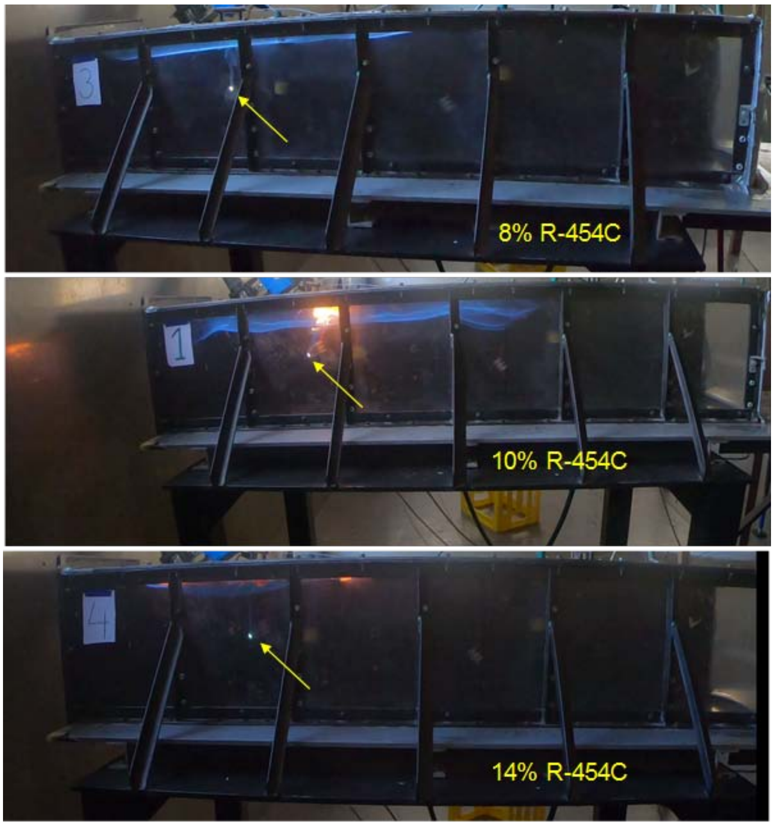


Figure 5.2: Premixed R-454C/air ignition tests to verify ignition source strength.

The location of the ignitors varied slightly during the testing campaign to ensure ignition. The external release R-290 tests were performed first so that we could verify that results were similar to what was seen in the FPRF R-290 tests. After performing a few commissioning tests with external R-454C releases, we decided to move the electrodes slightly and rotate them so that the spark gap was at the highest point. This was done to prevent the plastic electrode housing (see Figure 5.5) from being in direct contact with the initial flames that formed. Furthermore, a third ignitor configuration was used during internal release tests as described below to optimize ignition.

In the external R-290 release tests shown in Table 5.1, two ignitors were hung from the ceiling and secured to two poles positioned in front of the display case as shown in Figure 5.3 and Figure 5.5. The ignitor on the pole farther away from the display case was triggered first and caused ignition in all tests, thus the second ignitor was never triggered. In all tests, the first ignitor was triggered approximately 10 seconds after the release ended.

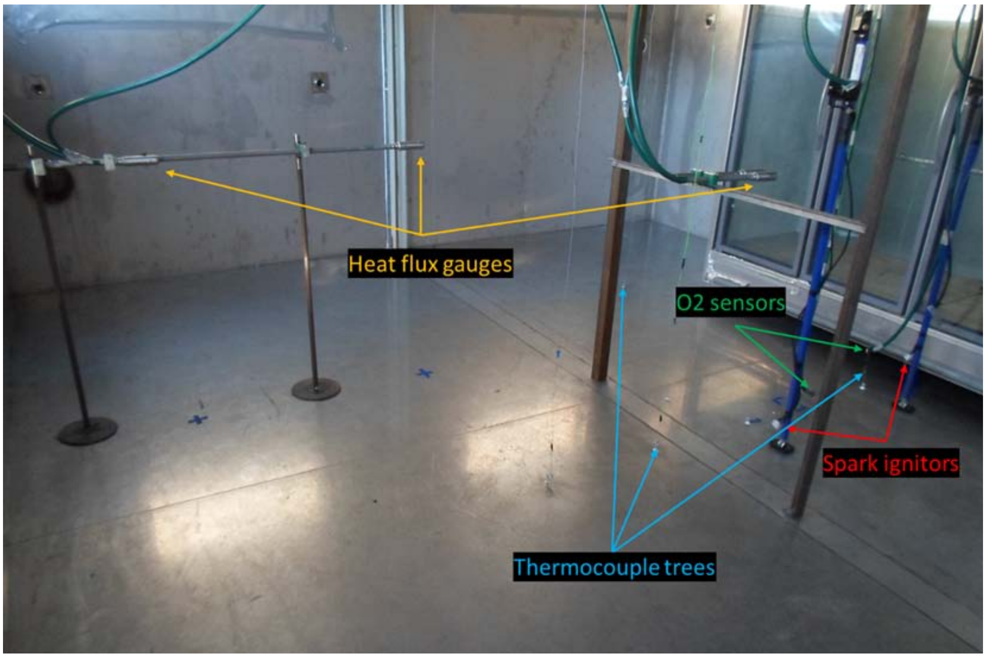


Figure 5.3: Test setup during external R-290 tests.

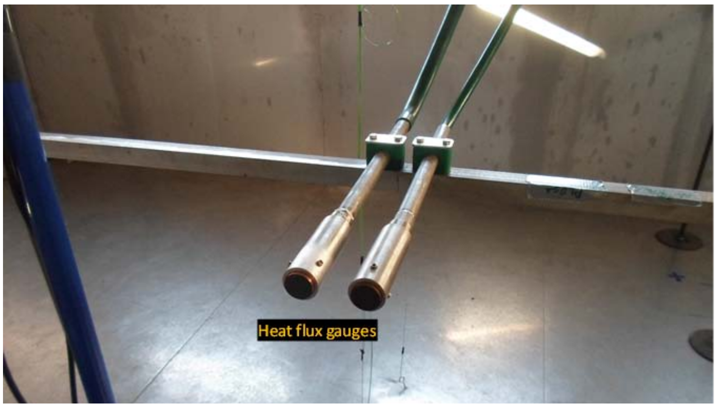


Figure 5.4: Heat flux gauges - one with a high range and fast response time and one with a lower range and slower response time.

Figure 5.5: Spark ignitor setup during external R-290 release tests (left image) and external R-454C release tests (right image).

In the external release R-454C tests shown in Table 5.1, three ignitors were used, and the electrode spark gaps were placed at optimal positions to ensure ignition: either at 3 cm, 5 cm, and 7 cm above the ground (see Figure 5.6 and Figure 5.7), or at 3 cm, 5 cm, and 15 cm above the ground (see Figure 5.8). The ignitors were energized one at a time for 10 seconds starting with the middle, lowest, then highest location. This sequence was repeated three times and then all three ignitors were energized at the same time for 10 seconds. In all tests, the first ignitor was triggered approximately 10 seconds after the release ended.

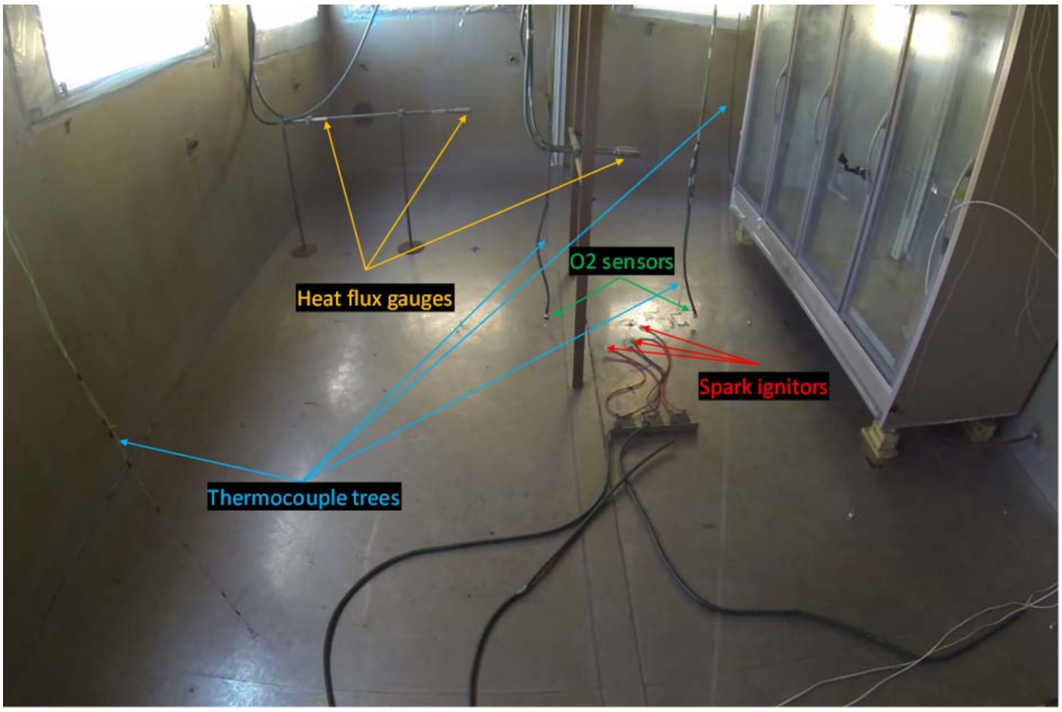


Figure 5.6: Test setup during external R-454C tests.

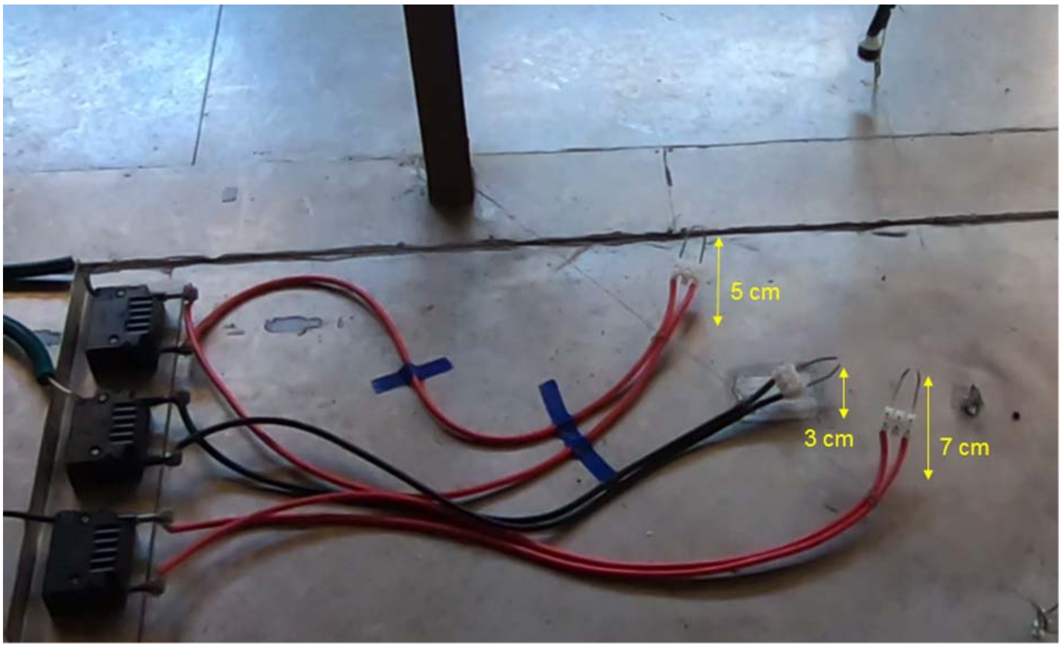


Figure 5.7: Spark ignitor setup during external R-454C release tests.

During all in-cabinet release tests (Table 5.2), the spark gaps were placed in front of the display case at 3 cm, 5 cm, and 15 cm above the ground (see Figure 5.8). Approximately 10 seconds after the release inside the display case was finished, all three ignitors were triggered. Then, about 5 seconds later, one of the display case doors was opened and the ignitors were left on for approximately 4 minutes.

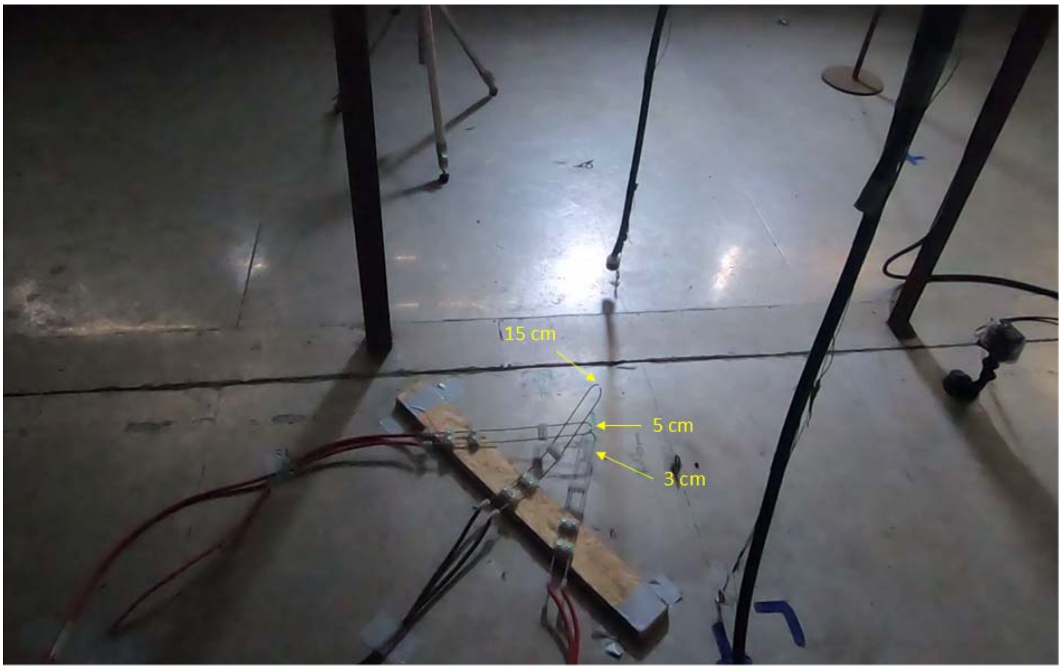


Figure 5.8: Spark ignitor setup during internal release tests.

During the free jet releases (Table 5.3), a pilot propane torch was placed near the release point like what was done in the PFRF R-290 tests. Tests were performed outside in order to minimize potential acid gas production inside the test enclosure.

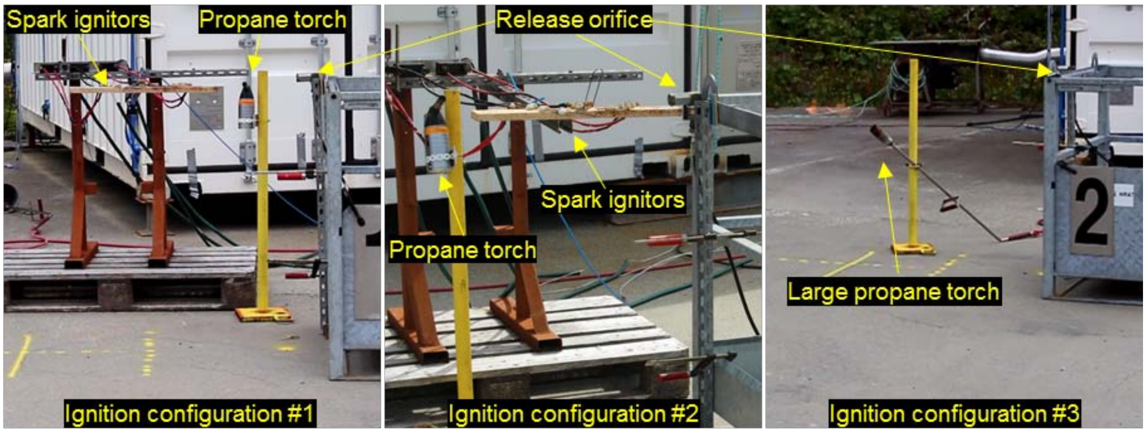


Figure 5.9: Free jet release tests to evaluate the potential severity of jet flames. Tests were performed with three different ignition source configurations.

5.2 Discussion regarding testing approach and results

Prior to presenting the results, it is necessary to reiterate that an objective of the study was to explore near-worst-case ignition consequences for certain refrigerant charge sizes and release rates. To do so, we designed the test enclosure to provide a sealed, quiescent environment and we replicated feasible release conditions that were most likely to result in flammable concentrations within the test enclosure, and lastly, we placed ignition sources where the flammable concentrations were.

In terms of test enclosure design, the enclosure was well-sealed and insulated to reduce convective flows and to minimize air change rates in order to maximum refrigerant concentrations at the floor. There was no room ventilation system such as a central heating/AC system and therefore the test enclosure provided an extremely quiescent environment during releases. Typical conditioned spaces where display cases are located, such as convenience stores, restaurants, and kitchens, will have higher air change rates and ventilation-induced mixing. Hence, tests in the enclosure show the near-worst-case concentrations that could result during low-momentum releases. In summary, the following additional mechanisms that could induce mixing or reduce refrigerant concentrations in actual settings where display cases were not present during testing: (1) room ventilation; (2) gaps in the room envelop; (3) additional mechanically induced airflow from other equipment in the room, such as neighboring display cases that could have condenser fans running; (4) airflow induced by occupants walking around; and (5) thermal convection currents.

For tests simulating releases inside a condensing unit, we purposely created highly impinged, low-momentum releases. Hence, the outcomes of the releases in terms of flammable cloud formation are considered representative of highest concentration layer cases since not all releases within a condensing unit will be as highly impinged. Recall that it is also plausible to have releases in a condensing unit that do not impinge on a surface or impinge farther away from the release point, however these scenarios were not considered during testing as they are less likely to result in flammable concentrations in the test room [2, 3].

For these reasons, the results presented below are not representative of all events that could occur when R-454C or R-290 leaks from a piece of equipment and an ignition source is or becomes present. Furthermore, the results do not indicate that all releases with similar released masses and leak rates will result in the outcomes observed in the present testing as there are numerous other variables that ultimately affect the outcome. For instance, the results presented below are highly dependent on the volume and floor area of the test enclosure, hence there could be very different outcomes for identical release conditions in rooms that are smaller or larger.

5.3 Ignition and flame propagation summary

Table 5.4 summarizes the post-ignition events during the condensing unit release tests and Figure 5.10 gives an example of the different descriptions used to categorize the observed flame propagation. The severity during these tests with R-454C ranged from no ignition (result 1) to sustained flame propagation in the vicinity of the ignitors for roughly 1.5 minutes after the ignitors were turned off (result 3). In the R-290 tests, severity ranged from flames spreading radially across the floor and burning in front of the display case (result 4) to flames propagating throughout the room (result 5). During the R-290 tests, flames and fire lasted for only a few seconds. In most of the tests with R-454C, small flames burned above the ignitors and only lasted while the ignitors were energized. Temperature, pressure, heat flux data, and still shot images from each test are provided in the next section.

Table 5.4: Simulated condensing unit release results.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)	Result
1	R-454C	Bottom	Impinged jet - vapor	20	1200	Off	0.0045	1
2	R-454C	Bottom	Impinged jet - vapor	200	600	Off	0.0029	1
3	R-454C	Bottom	Impinged jet - vapor	200	1200	Off	0.0034	2
4	R-454C	Bottom	Impinged jet - vapor	200	2000	Off	0.0042	2
5	R-454C	Bottom	Impinged jet - vapor	200	2000	Off	0.0223	3
6	R-454C	Bottom	Impinged jet - vapor	200	1200	On	0.0044	1
7	R-454C	Bottom	Impinged jet - vapor	550	600	Off	0.0039	2
8	R-454C	Bottom	Impinged jet - vapor	550	1200	Off	0.0033	2
9	R-454C	Top	Impinged jet - vapor	200	2000	Off	0.0040	1
10	R-290	Bottom	Impinged jet - vapor	12	300	Off	< 0.0063	4
11	R-290	Bottom	Impinged jet - vapor	335	300	Off	< 0.0063	5
12	R-290	Bottom	Impinged jet - vapor	335	600	Off	< 0.0063	5
13	R-290	Bottom	Impinged jet - vapor	120	600	Off	< 0.0063	5
14	R-290	Top	Impinged jet - vapor	120	600	Off	< 0.0063	4

<u>Results key</u>

1 - No ignition

2 - Ignition with flames anchored to the ignitors which extinguished when ignitors were turned off

3 - Ignition with flames that slowly spread radially and continued to burn after ignitors were turned off

4 - Ignition with flame propagation across the floor and in front of display case

5 - Ignition with flame propagation throughout the room

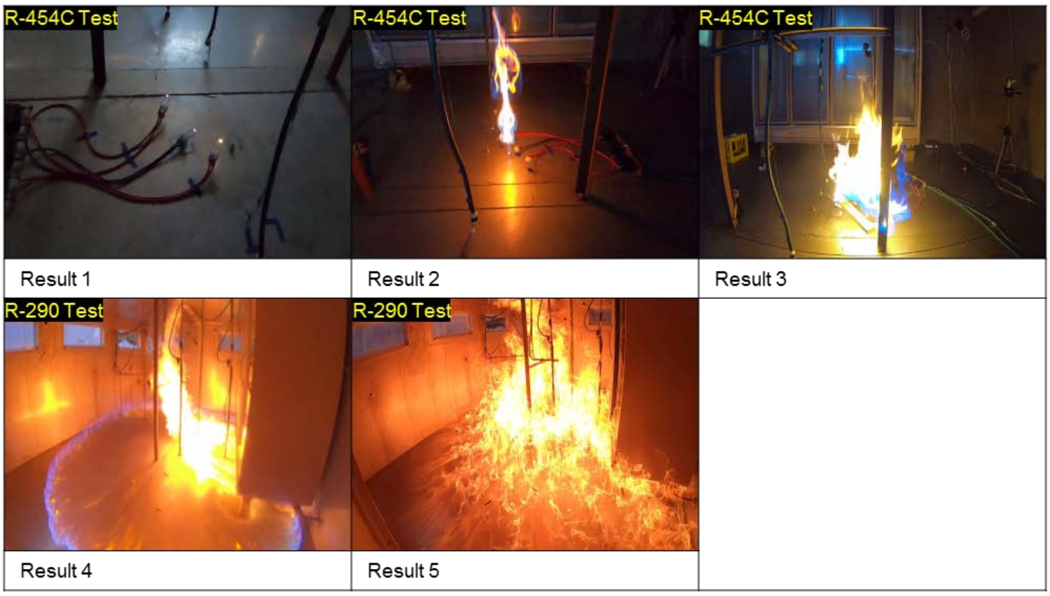


Figure 5.10: Example results categories during simulated condensing unit releases.

Table 5.5 summarizes the results for the releases inside the display case. The severity during tests with R-454C ranged from no ignition (result 1) to ignition and flame propagation along the floor (result 3). In the low-humidity R-454C tests that ignited, flames extended briefly from the ignitors when the door was first opened and only lasted for a few seconds (result 2). In Test #19 with higher humidity, flames moved quickly along the floor and briefly extended upward almost to the ceiling. Flames burned in the room for approximately 7 seconds before burning back into the display case.

Tests with R-290 resulted in ignition and a large ball of flames in and around the display case (result 4). In Test #20 with R-290, ignition occurred when the ignitor was first energized before the door was opened. R-290 leaked out of the display case during the release. When ignition occurred, a flame propagated into the display case and caused the door to open. Flames then extended out of the display case (result 3). In Test #21, ignition occurred after the display case door was opened, however the results were similar to what was observed in Test #20. Temperature data, pressure data, heat flux data, and still shot images from each test are provided in in the next section.

Table 5.5: Inside release results.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)	Result
15	R-454C	Inside	Free jet - vapor	200	900	Off	0.0040	1
16	R-454C	Inside	Impinged jet - vapor	200	900	Off	0.0055	2
17	R-454C	Inside	Free jet - vapor	200	1800	Off	0.0042	2
18	R-454C	Inside	Impinged jet - vapor	200	1800	Off	0.0045	2
19	R-454C	Inside	Free jet - vapor	200	1800	Off	0.0236	3
20	R-290	Inside	Impinged jet - vapor	120	900	Off	< 0.0063	4
21	R-290	Inside	Free jet - vapor	120	900	Off	< 0.0063	4

Results key

1 - No ignition

2 - Ignition with flow-induced transport of flames away from ignitors followed by flame extinction

3 - Ignition and flame propagation along the floor

4 - Ignition with large ball of flame in and around the display case

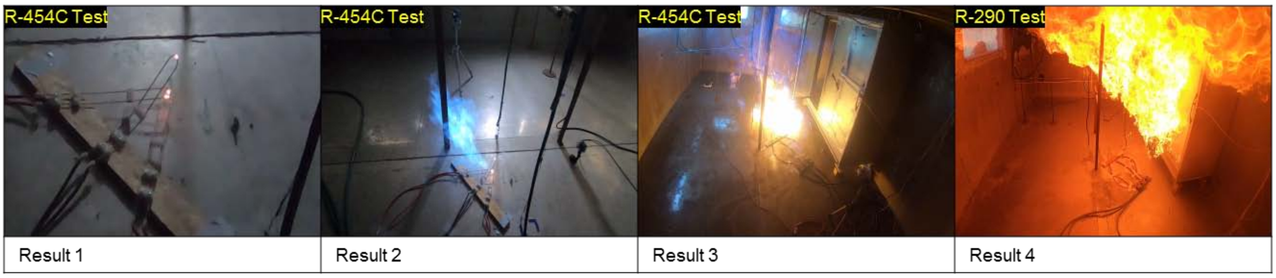


Figure 5.11: Example results categories during inside releases.

Table 5.6 provides the results for the free jet releases performed to evaluate jet flame severity. Ignition did not occur in either test with any of the three ignition source configurations.

Table 5.6: Results during free-jet releases to evaluate jet flame severity.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)	Result
22	R-454C	In front	Free jet - vapor	550	1000	Off	< 0.0063	1
23	R-454C	In front	Free jet - liquid	4450	1000	Off	< 0.0063	1

Results key

1 - No ignition

5.4 Results Overview

This section provides the measured data during each test, which included; the refrigerant concentration up until the end of the release at two points near the ignitors; the pressure inside the room after the ignitors were energized; the temperature at the 12 thermocouple positions shown in Figure 5.1; the heat flux at the gauges shown in Figure 5.1; and still shot images showing the inside the test enclosure shortly after the first ignitor was energized and when the fire size was largest.

For the condensing unit releases, concentrations at the end of the releases were similar to those measured during the dispersion tests discussed above in Section 4. During the testing campaign, the sensors were moved to positions different than the positions in the dispersion tests and therefore direct comparisons could not be made. Nonetheless, the various test repeats performed during this study showed that the dispersion results were very repeatable in the new test enclosure.

Pressure rise was limited in all tests by the presence of the vent openings covered with plastic sheets. In the R-290 tests, the peak pressure rise ranged from 0.2 psig to 0.4 psig and the pressure increased from ambient to maximum in less than one second. There was no pressure rise during the low-humidity R-454C tests. In Test #5 with higher humidity, the room pressure slowly increased over a period of approximately 25 seconds to a maximum of 0.35 psig and then one of the plastic vent sheets yielded. In Test #19 with higher humidity, the peak pressure rise was 0.25 psig and the pressure increased from ambient to maximum in close to one second. The slight variations in peak pressure between these tests is the result of slight variations in the yield pressure of the plastic sheets.

As expected, measured temperatures correlated with flame size and duration. A peak temperature of 1400 °F was measured during R-290 ignition tests and a peak temperature of 210 °F and 1150 °F were measured during Tests #5 and #19 with R-454C in humid air.

Measured heat fluxes also correlated with flame size and duration. A peak value of approximately 250 kW/m^2 was measured at the sensor closest to the ignition point during the most severe R-290 test. Note that the new sensors recorded peak heat fluxes roughly a factor of 2-5 higher than the low range sensors because of their much faster response times. The fast, high range sensors provided accurate measurement of the high heat fluxes during the R-290 tests whereas the lower range sensors provided the heat fluxes during the R-454C tests.

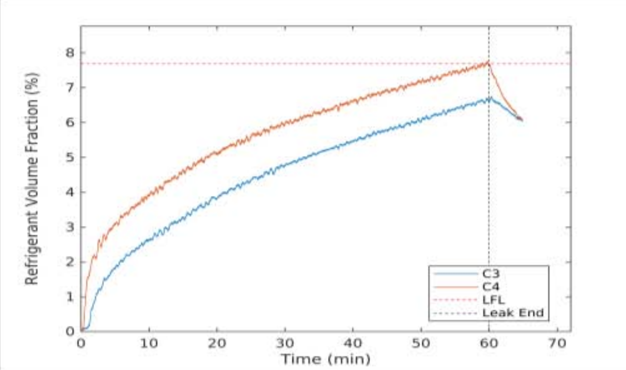
Measured peak heat fluxes reached a maximum of 1 kW/m^2 during Test #5 with R-454C in higher-humidity air. In Test #18 with R-454C, a peak heat flux of 3 kw/m^2 was recorded at the sensor closest to the ignition point (i.e., Location #1) and it appears from the video that a flame briefly passed directly in front of the heat flux gauge and hence the briefly higher recorded heat flux although the flames were smaller and shorter in duration compared to in Test #5. In Test #19 with R-454C in higher-humidity air, peak heat fluxes at the sensor closest to the ignition location briefly reached 150 kW/m^2. Note however that while this value is comparable to the peak heat fluxes at this sensor during tests with R-290, the heat fluxes at the sensor farthest away from the ignition point (Location #3) were much lower. This is because the overall fire size was still smaller in Test #19 compared to the R-290 tests.

Presented below are the results from each of the 23 ignition tests.

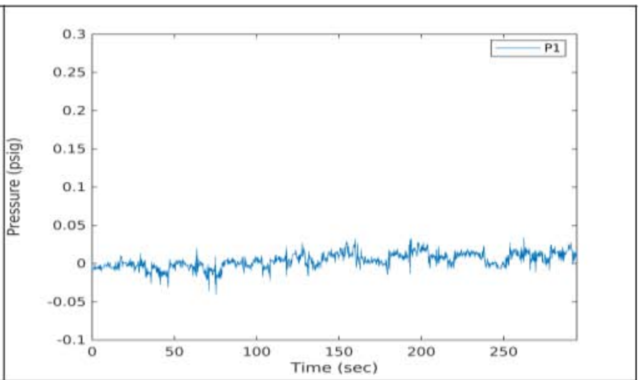
Table 5.7: Test #1 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
1	R-454C	Bottom	Impinged jet - vapor	20	1200	Off	0.0045

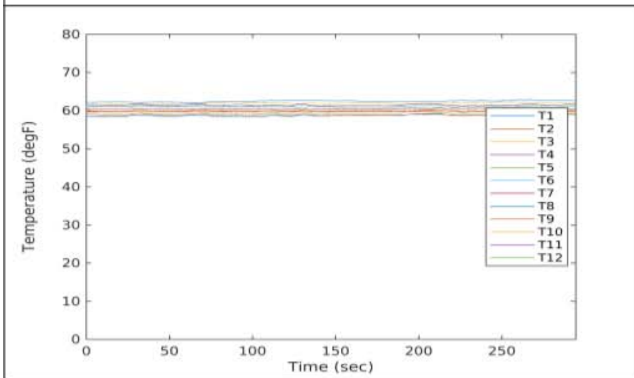
Ignition did not occur in Test #1. Recall that during the external release tests, the ignitors were energized one at a time for 10 seconds starting with the 5 cm, then the 3 cm, then the 7 cm location. This sequence was repeated three times and then all three ignitors were energized at the same time for 10 seconds. Furthermore, in these tests, the first ignitor was triggered approximately 10 seconds after the release ended.



Refrigerant concentration until leak end



Pressure after ignitor first energized



Temperature after ignitor first energized

No measured increase.

Heat flux after ignitor first energized

Image 1

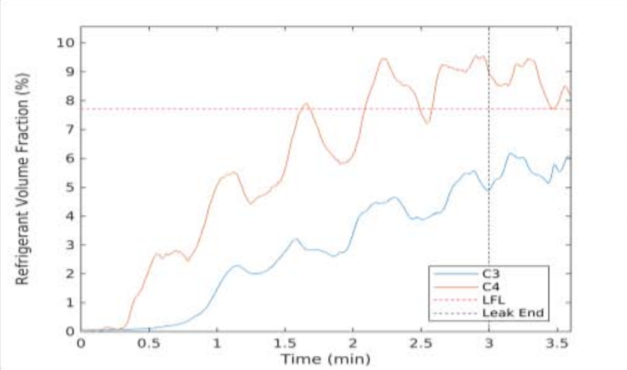
Image 2

Figure 5.12: Data for Test #1.

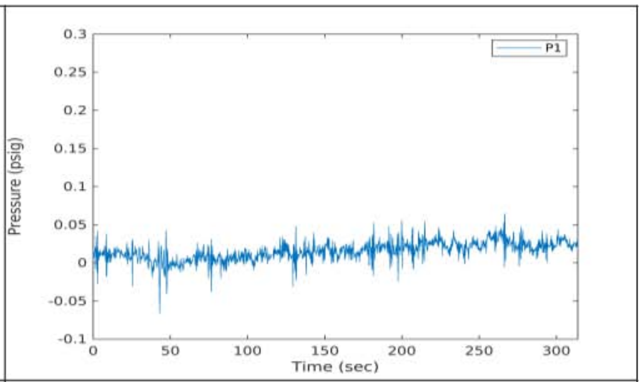
Table 5.8: Test #2 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
2	R-454C	Bottom	Impinged jet - vapor	200	600	Off	0.0029

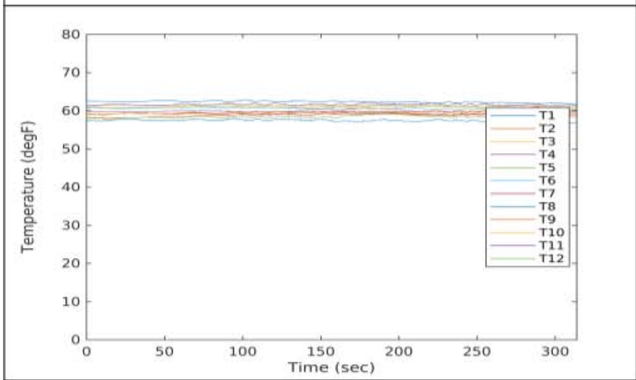
Ignition did not occur in Test #2.



Refrigerant concentration until leak end



Pressure after ignitor first energized



Temperature after ignitor first energized

No measured increase.

Heat flux after ignitor first energized

Image 1

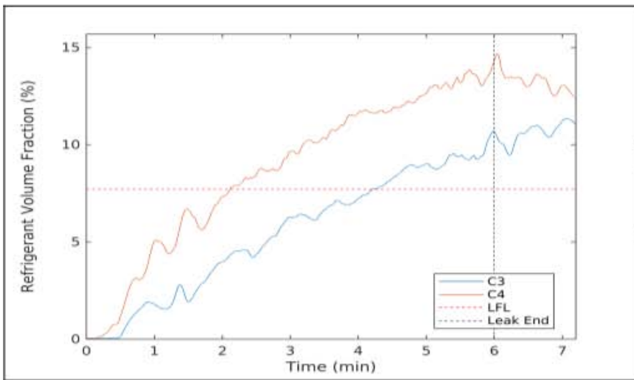
Image 2

Figure 5.13: Data for Test #2.

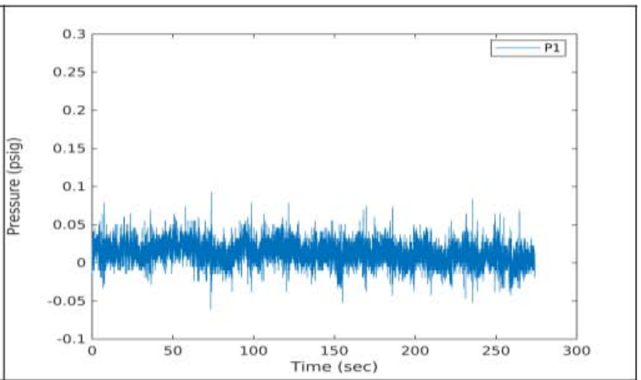
Table 5.9: Test #3 conditions

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
3	R-454C	Bottom	Impinged jet - vapor	200	1200	Off	0.0034

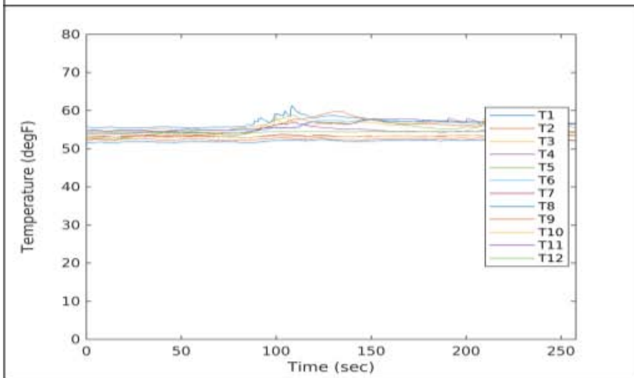
Ignition occurred in Test #3, with small flames anchored to the ignitors while they were energized. When the ignitors were turned off, the flames extinguished.



Refrigerant concentration until leak end



Pressure after ignitor first energized



Temperature after ignitor first energized

Maximum increase less than 0.1 kW/m^2.

Heat flux after ignitor first energized

Image 1

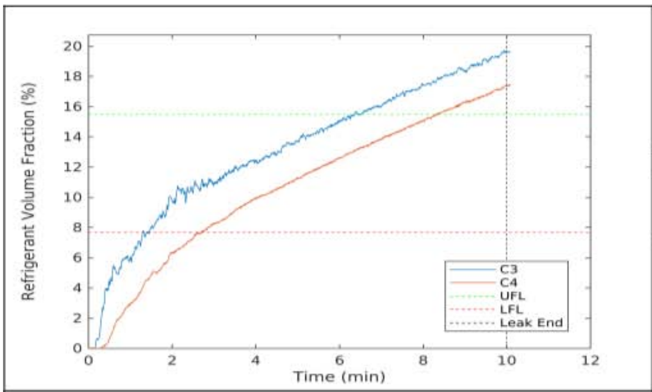
Image 2

Figure 5.14: Data from Test #3.

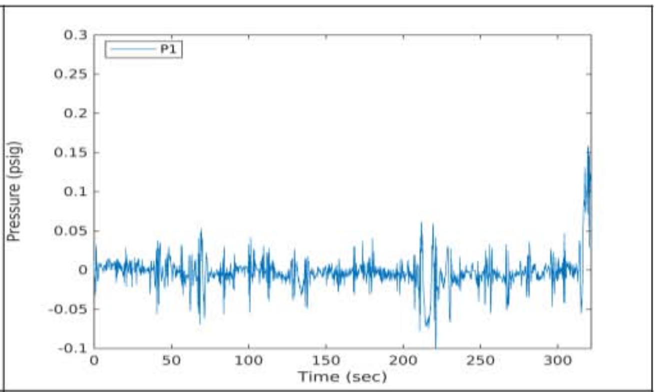
Table 5.10: Test #4 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
4	R-454C	Bottom	Impinged jet - vapor	200	2000	Off	0.0042

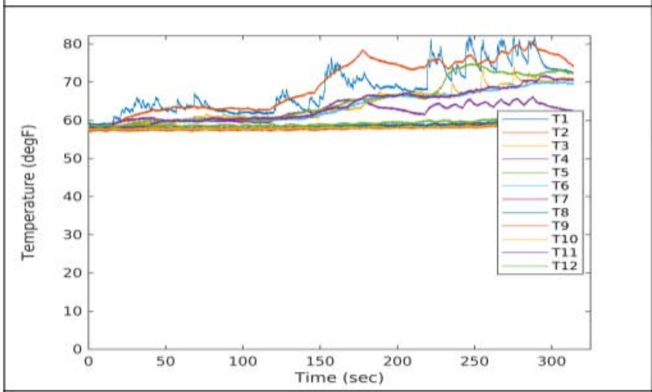
Ignition occurred in Test #4, with slightly larger flames (compared to Test #3) anchored to the ignitors while they were energized. When the ignitors were turned off, the flames extinguished.



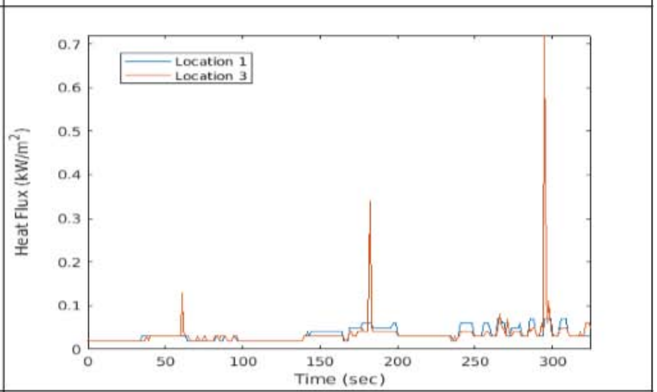
Refrigerant concentration until leak end



Pressure after ignitor first energized



Temperature after ignitor first energized



Heat flux after ignitor first energized

Image 1

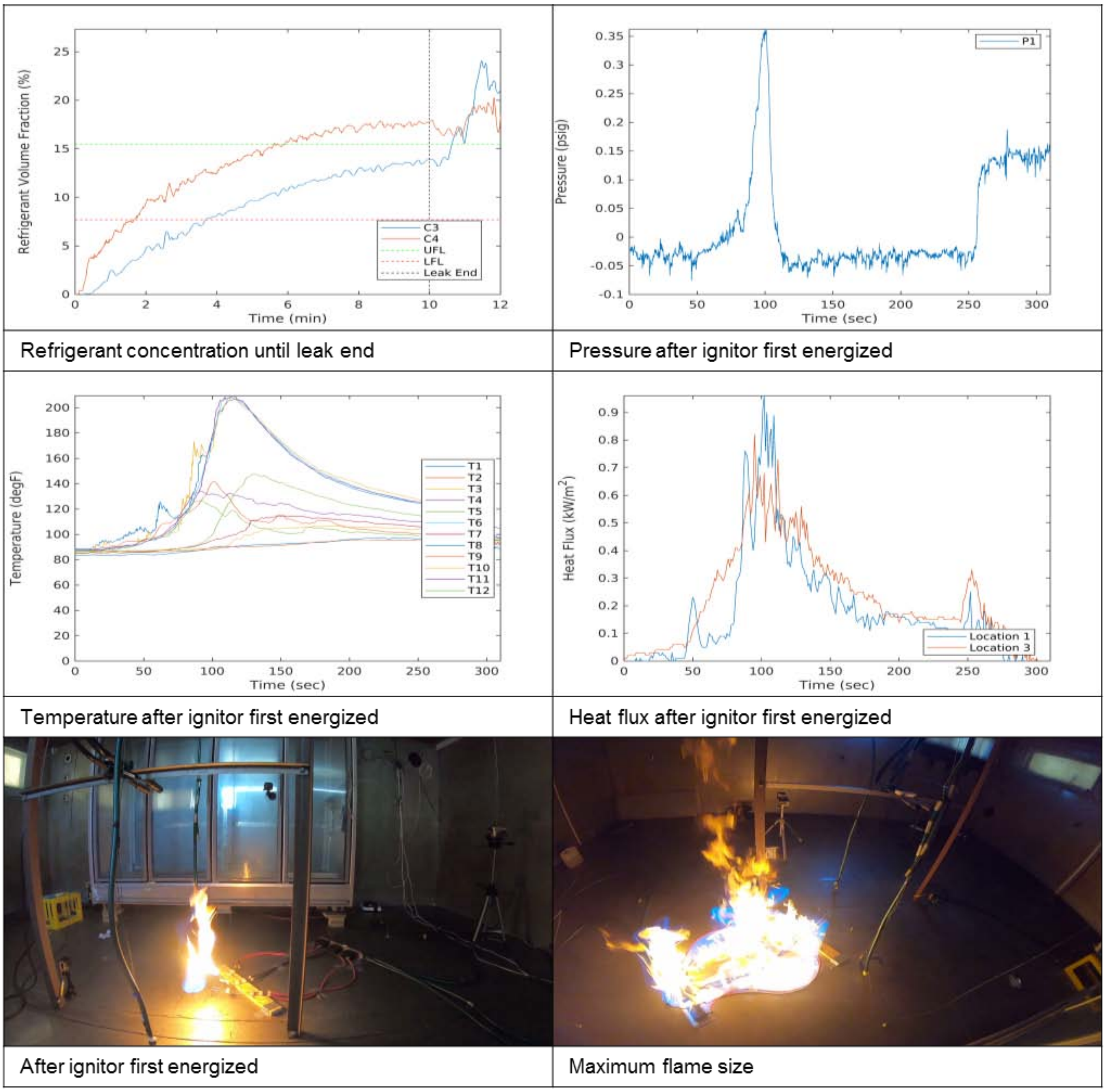
Image 2

Figure 5.15: Data from Test #4.

Table 5.11: Test #5 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
5	R-454C	Bottom	Impinged jet - vapor	200	2000	Off	0.0223

Test #5 was a repeat of Test #4, but in higher-humidity air. Ignition occurred in Test #5, with a flame stationary at the ignitor location during the first 30 seconds after ignition while the ignitor was still energized. When the ignitor was turned off, the flames slowly spread radially and downward until they contacted the equipment and cabling along the ground as seen in Figure 5.17. During the most intense burning, the flame height reached approximately 3 feet (1 m). In total, the flames lasted for approximately 110 seconds.



Refrigerant concentration until leak end

Pressure after ignitor first energized

Temperature after ignitor first energized

Heat flux after ignitor first energized

After ignitor first energized

Maximum flame size

Figure 5.16: Data for Test #5.

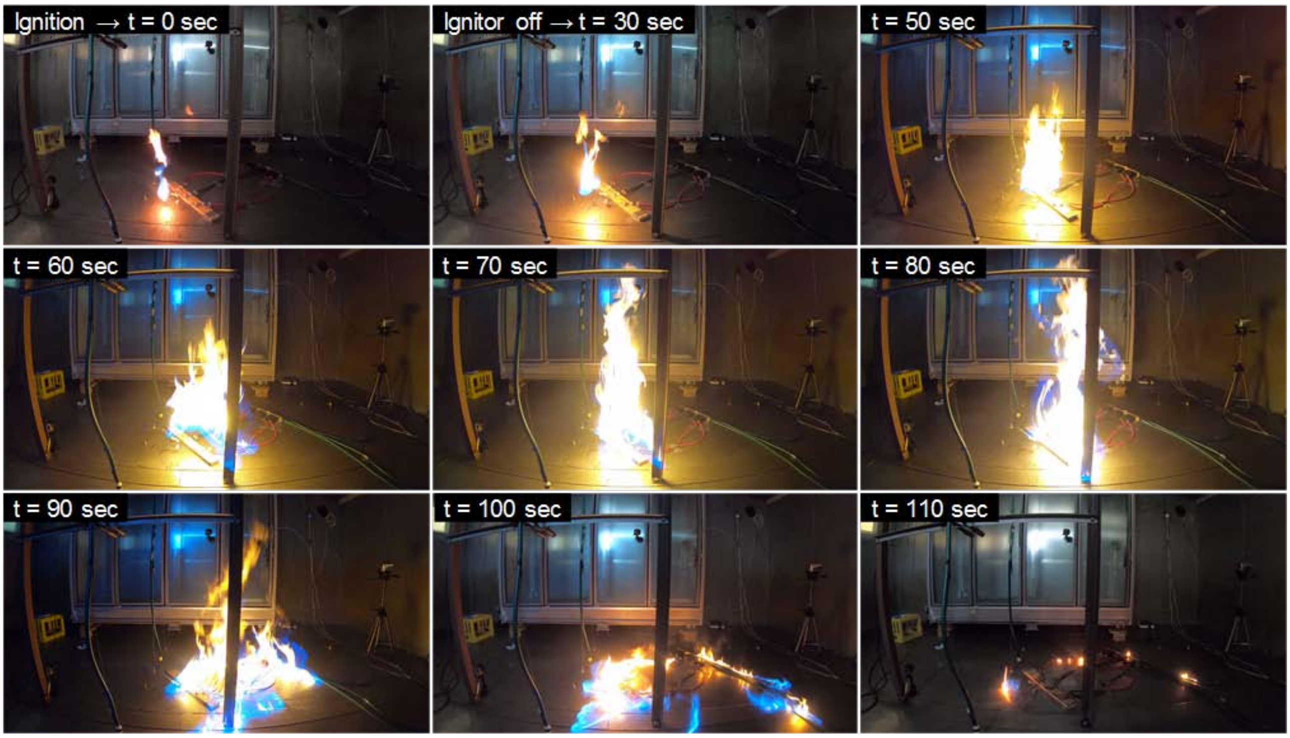
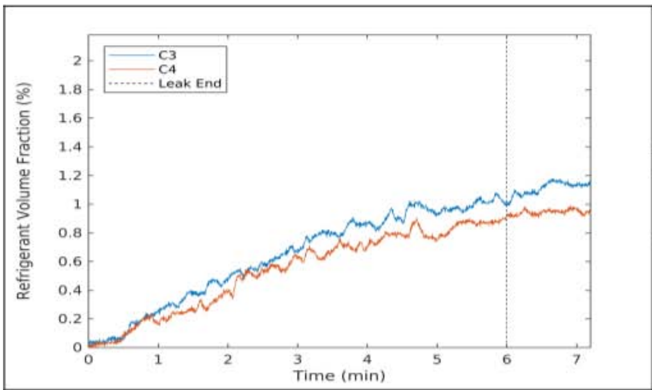


Figure 5.17: Test #5 flame evolution after ignition.

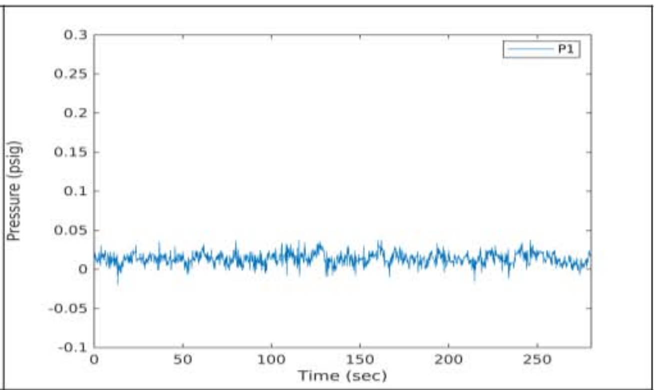
Table 5.12: Test #6 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
6	R-454C	Bottom	Impinged jet - vapor	200	1200	On	0.0044

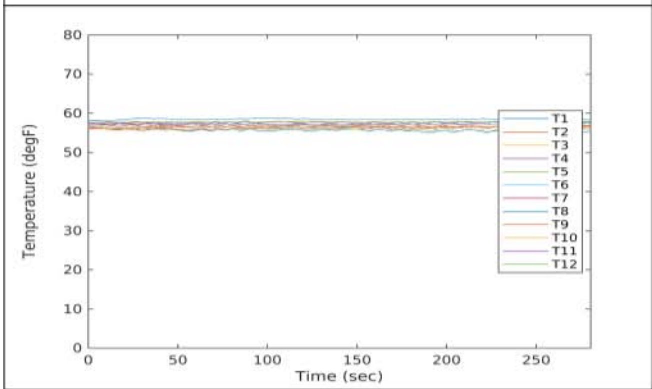
Ignition did not occur in Test #6.



Refrigerant concentration until leak end



Pressure after ignitor first energized



Temperature after ignitor first energized

No measured increase.

Heat flux after ignitor first energized

Image 1

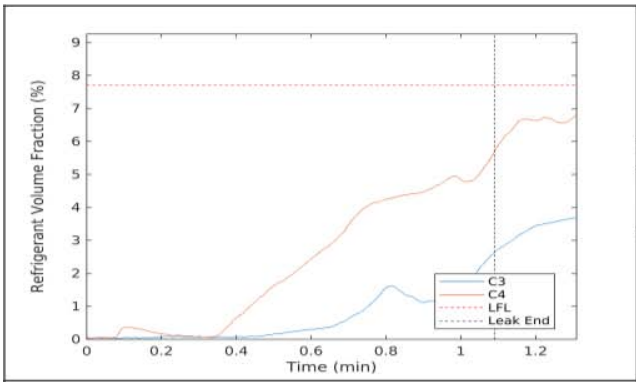
Image 2

Figure 5.18: Data for Test #6.

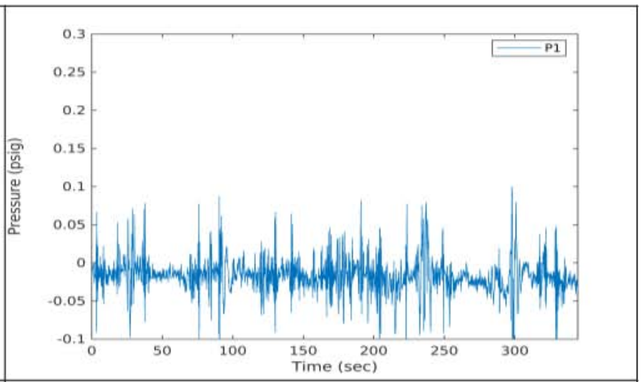
Table 5.13: Test #7 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
7	R-454C	Bottom	Impinged jet - vapor	550	600	Off	0.0039

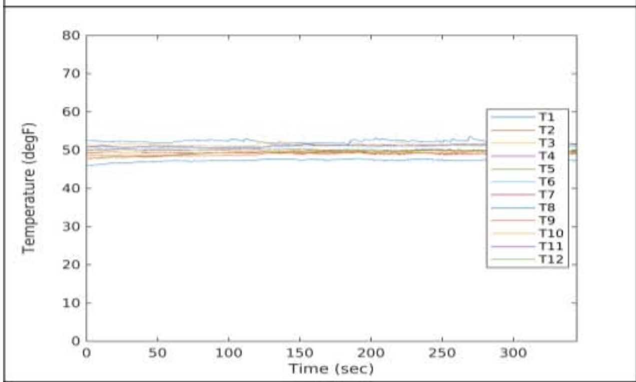
Ignition occurred in Test #7, with small flames anchored to the ignitors while they were energized. When the ignitors were turned off, the flames extinguished.



Refrigerant concentration until leak end



Pressure after ignitor first energized



Temperature after ignitor first energized

Maximum increase less than 0.1 kW/m^2.

Heat flux after ignitor first energized

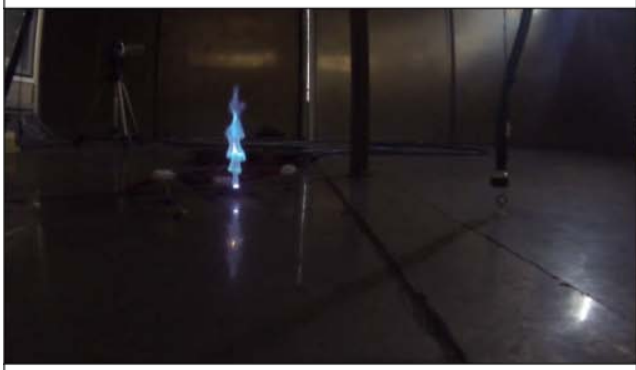


Image 1

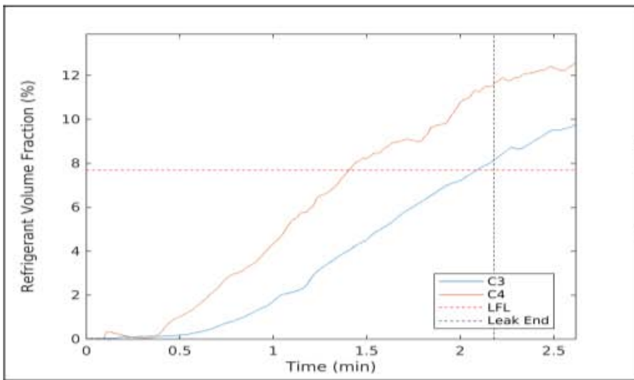
Image 2

Figure 5.19: Data for Test #7.

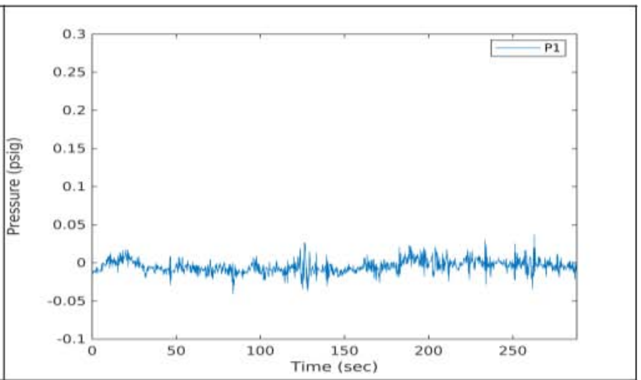
Table 5.14: Test #8 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
8	R-454C	Bottom	Impinged jet - vapor	550	1200	Off	0.0033

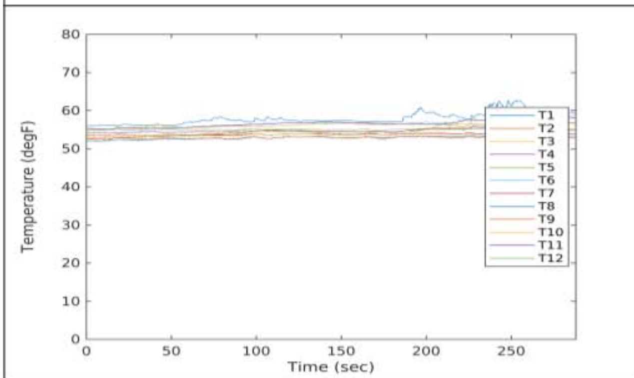
Ignition occurred in Test #8, with small flames anchored to the ignitors while they were energized. When the ignitors were turned off, the flames extinguished.



Refrigerant concentration until leak end



Pressure after ignitor first energized



Temperature after ignitor first energized

Maximum increase less than 0.15 kW/m^2.

Heat flux after ignitor first energized

Image 1

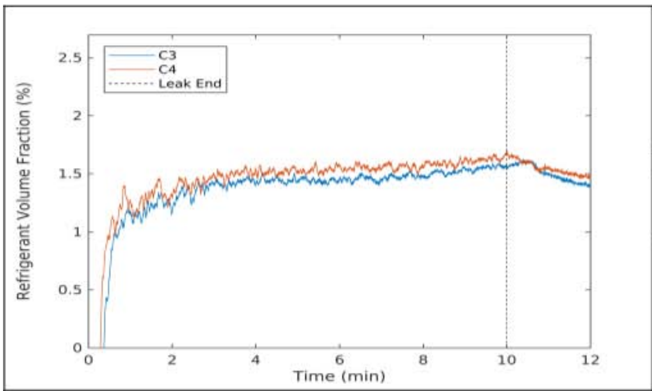
Image 2

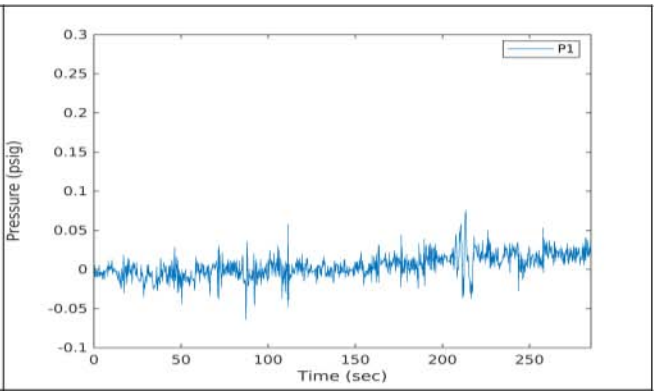
Figure 5.20: Data for Test #8.

Table 5.15: Test #9 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
9	R-454C	Top	Impinged jet - vapor	200	2000	Off	0.0040

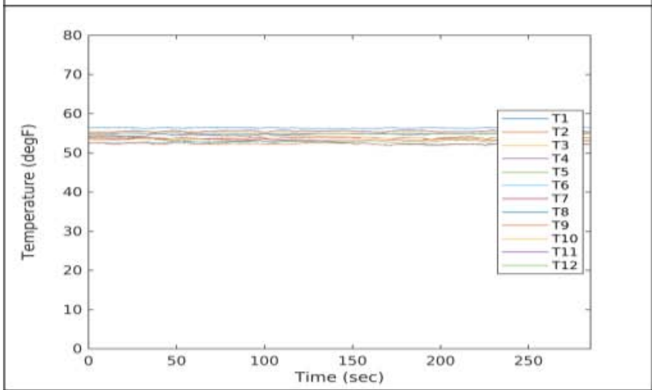
Ignition did not occur in Test #9.





Refrigerant concentration until leak end

Pressure after ignitor first energized



No measured increase.

Temperature after ignitor first energized

Heat flux after ignitor first energized

Image 1

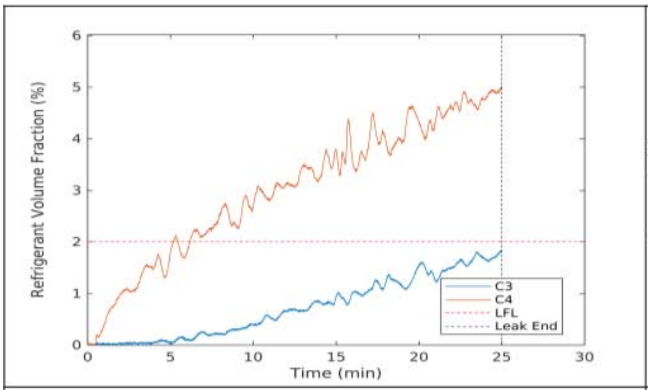
Image 2

Figure 5.21: Data for Test #9.

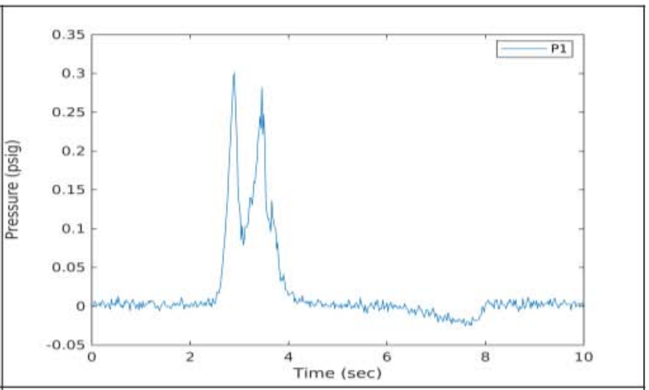
Table 5.16: Test #10 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
10	R-290	Bottom	Impinged jet - vapor	12	300	Off	< 0.0063

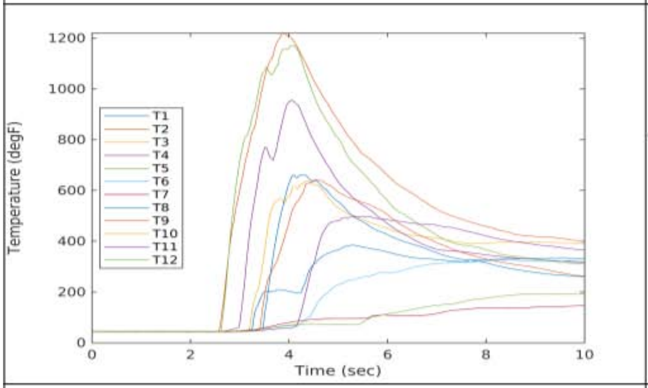
Ignition occurred in Test #10, with flames propagating across the floor and burning in front of the display case. The flames lasted for approximately 2 seconds after ignition.



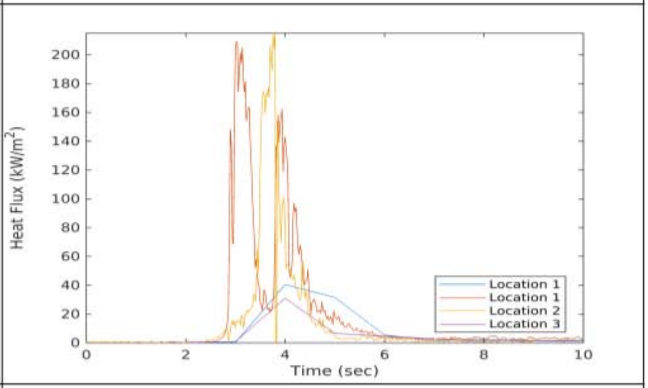
Refrigerant concentration until leak end



Pressure after ignition



Temperature after ignition



Heat flux after ignition

Image 1

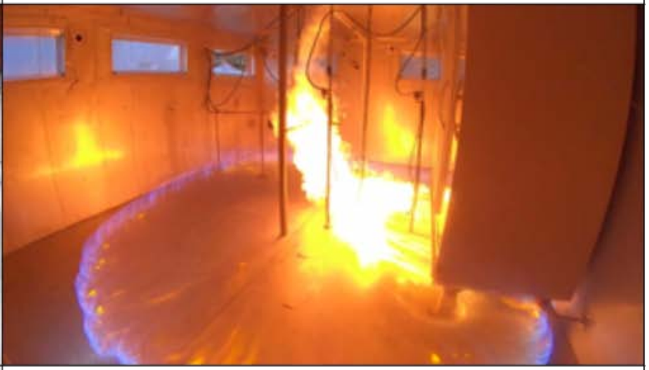


Image 2

Figure 5.22: Data for Test #10.

Table 5.17: Test #11 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
11	R-290	Bottom	Impinged jet - vapor	335	300	Off	< 0.0063

Ignition occurred in Test #11, with flames propagating throughout the room. The flames lasted for approximately 3-4 seconds after ignition.

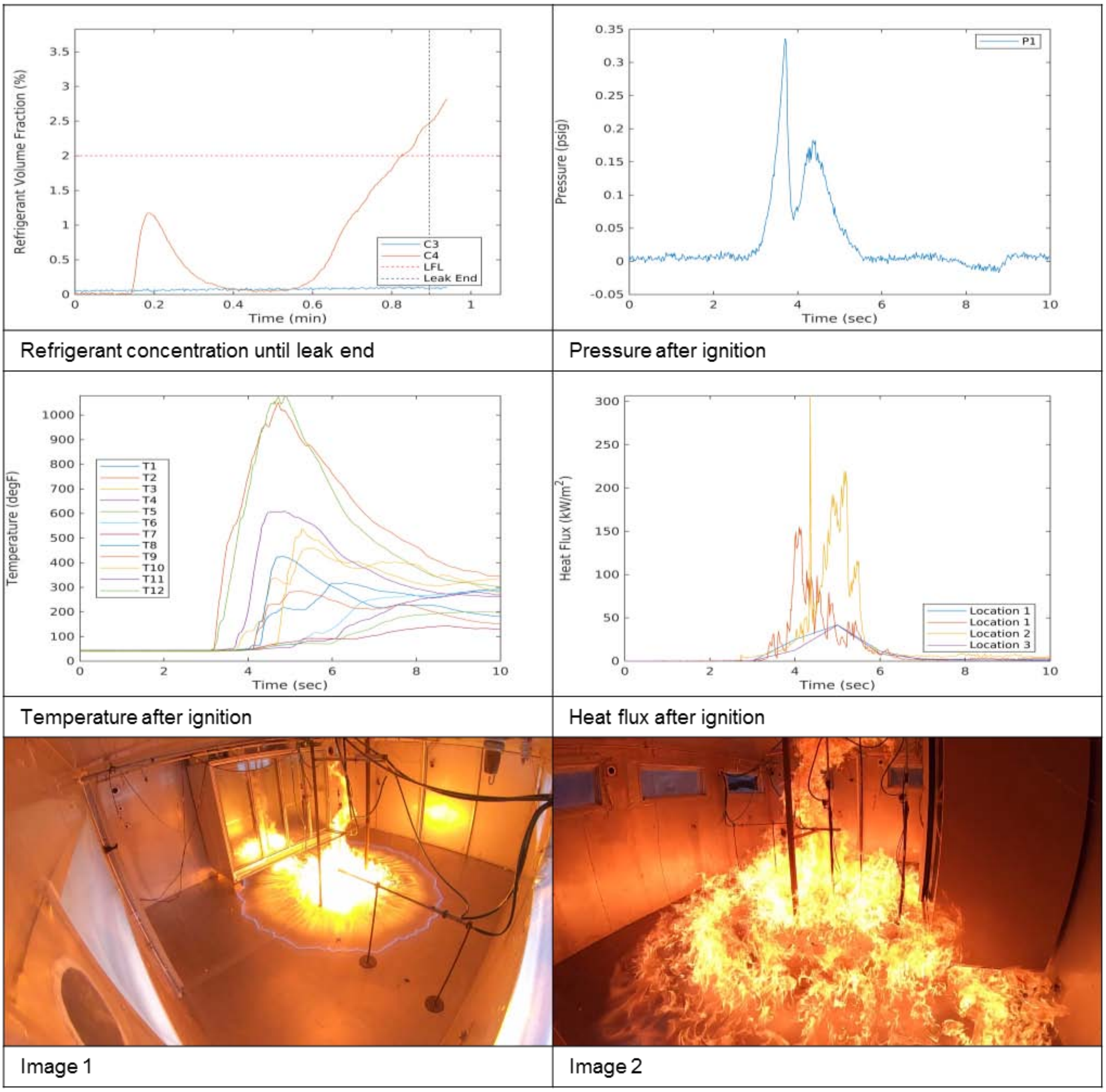
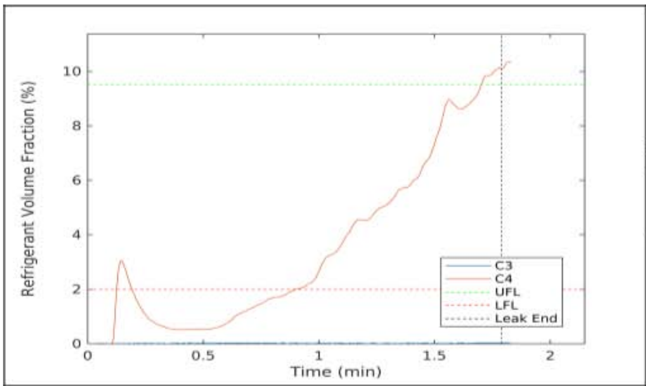


Figure 5.23: Data for Test #11.

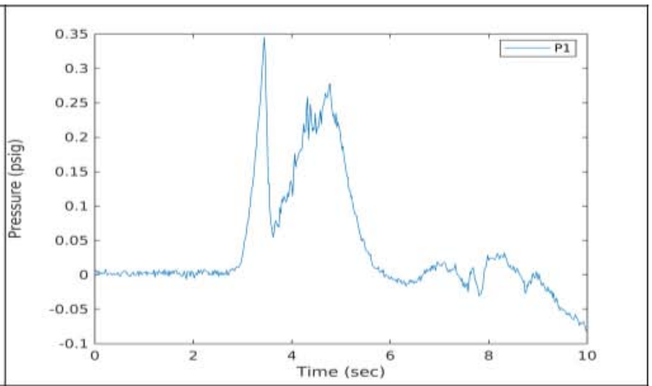
Table 5.18: Test #12 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
12	R-290	Bottom	Impinged jet - vapor	335	600	Off	< 0.0063

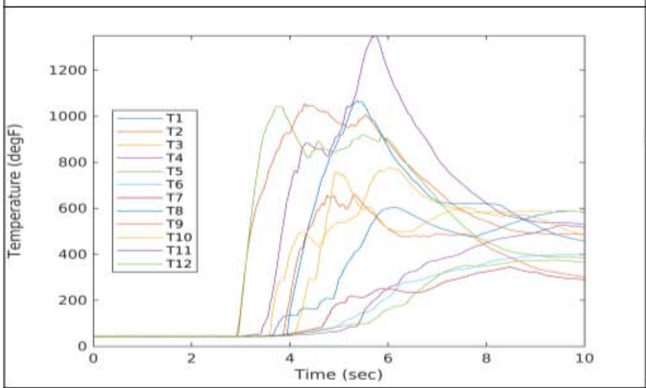
Ignition occurred in Test #12, with flames propagating throughout the room. The flames lasted for approximately 4-5 seconds after ignition.



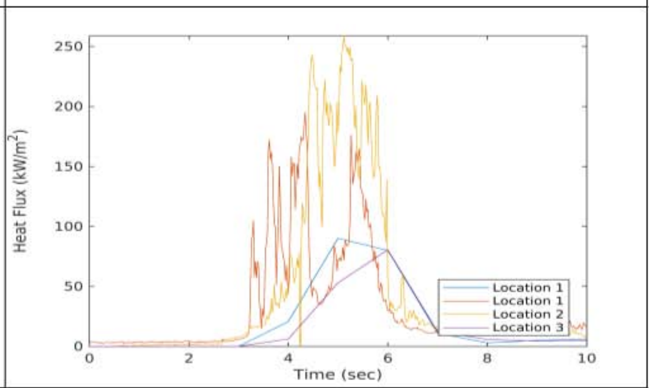
Refrigerant concentration until leak end



Pressure rise after ignition



Temperature after ignition



Heat flux after ignition

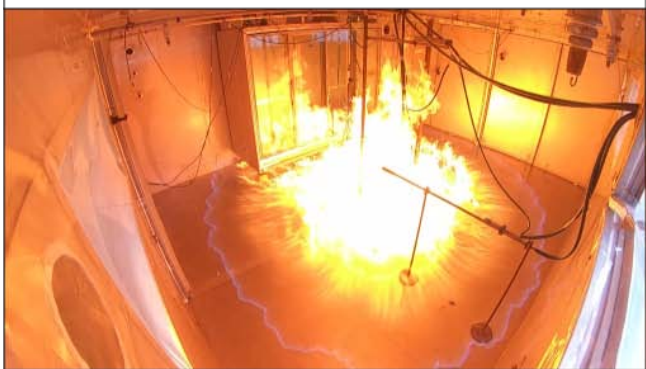


Image 1

Image 2

Figure 5.24: Data for Test #12.

Table 5.19: Test #13 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
13	R-290	Bottom	Impinged jet - vapor	120	600	Off	< 0.0063

Ignition occurred in Test #13, with flames propagating throughout the room. The flames lasted for approximately 4-5 seconds after ignition.

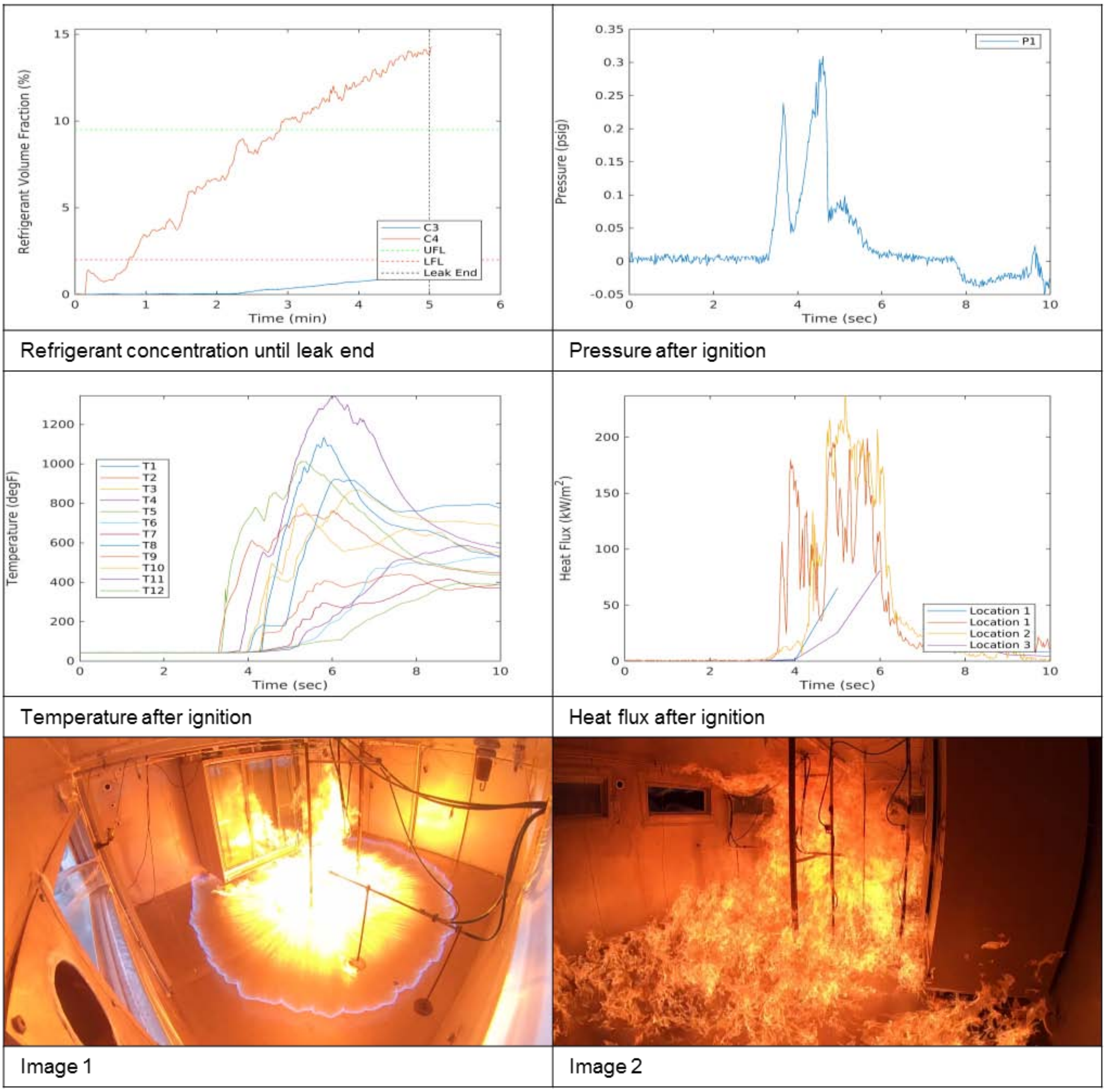
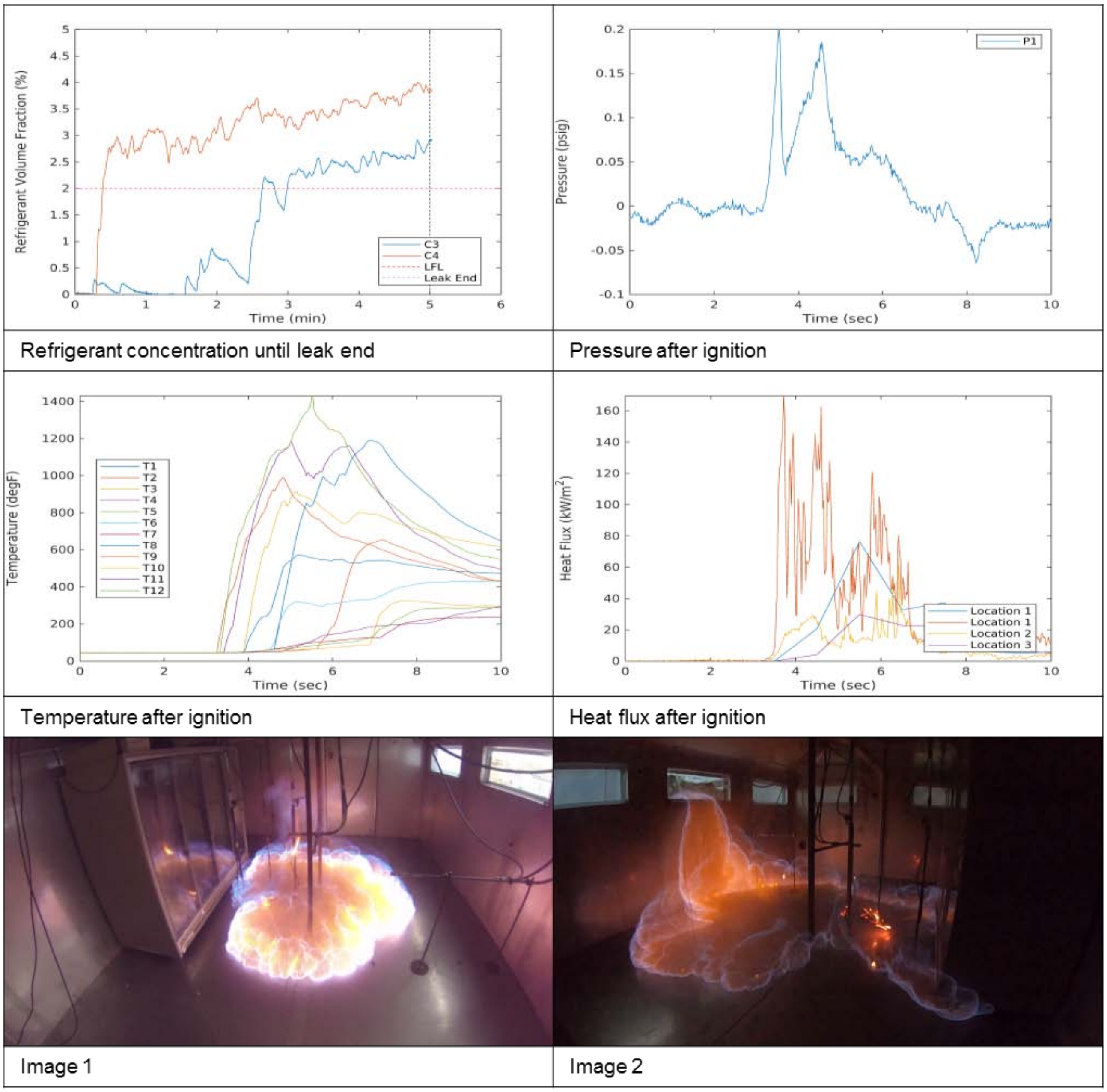


Figure 5.25: Data for Test #13.

Table 5.20: Test #14 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
14	R-290	Top	Impinged jet - vapor	120	600	Off	< 0.0063

Ignition occurred in Test #14, with flames propagating throughout the lower portion of the room and out one of the vent openings. The flames lasted for approximately 3-4 seconds after ignition.



Refrigerant concentration until leak end

Pressure after ignition

Temperature after ignition

Heat flux after ignition

Image 1

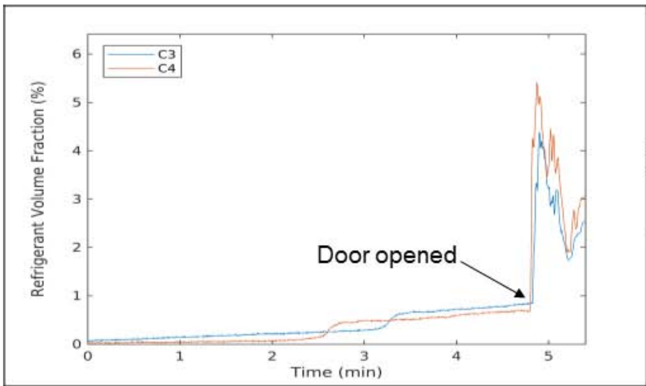
Image 2

Figure 5.26: Data for Test #14.

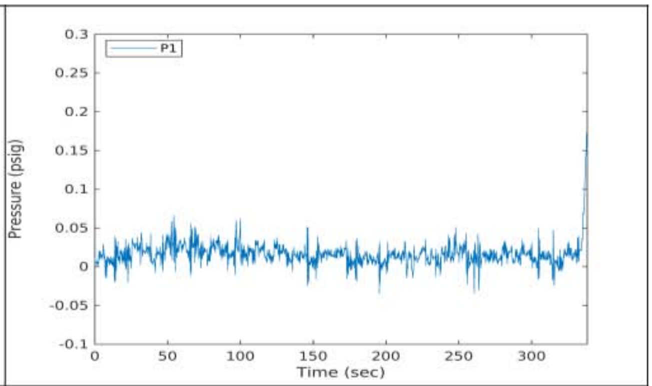
Table 5.21: Test #15 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
15	R-454C	Inside	Free jet - vapor	200	900	Off	0.0040

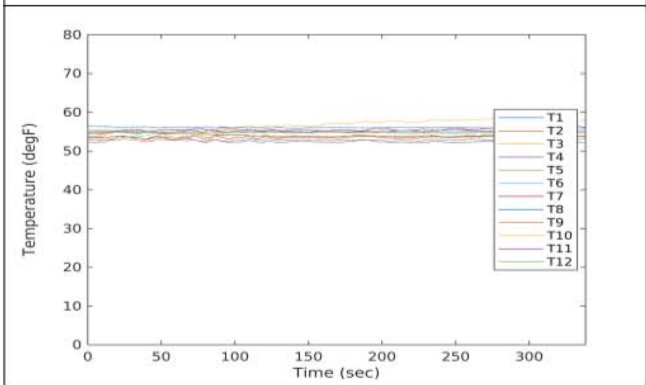
Ignition did not occur in Test #15. Recall that in the internal release tests, approximately 10 seconds after the release inside the display case ended, all three ignitors were triggered. Approximately 5 seconds later, one of the display case doors was opened and the ignitors were left energized for about 4 minutes. As the concentration sensor measurements show, refrigerant leaked out of the display case while the internal release was underway and before the door was opened. If there was no leakage from the cabinet during the release and uniform mixing (via the free jet release), the concentration of R-454C in the cabin would have been approximately 5% by volume and below the reported LFL of 7.7%. The actual concentration was lower due to the leakage.



Refrigerant concentration until leak end



Pressure after ignitor first energized



Temperature after ignitor first energized

No measured increase.

Heat flux after ignitor first energized

Image 1

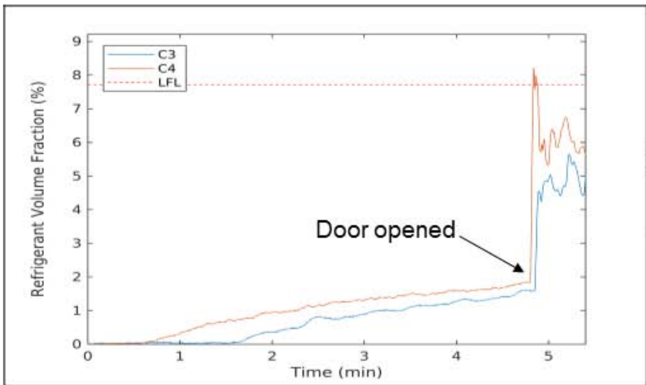
Image 2

Figure 5.27: Data for Test #15.

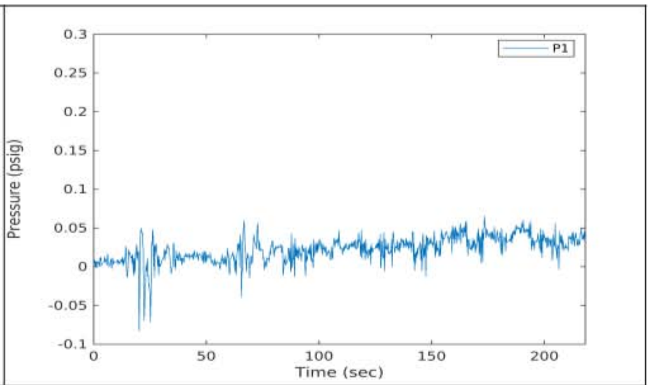
Table 5.22: Test #16 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
16	R-454C	Inside	Impinged jet - vapor	200	900	Off	0.0055

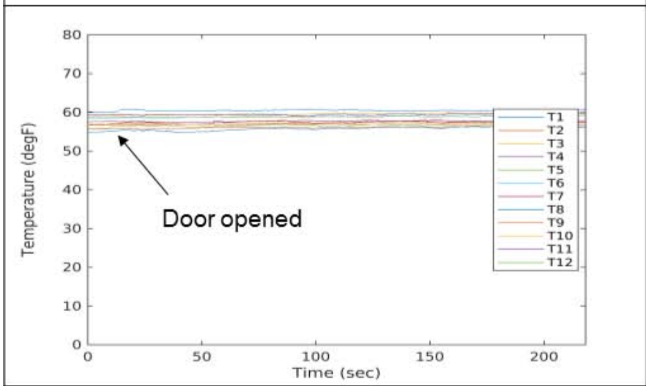
Ignition occurred in Test #16, with a very small flame briefly extending from the lowest ignitor shortly after the display case door was opened. The small flame is shown in image 1 in the figure below. As during Test #15, refrigerant leaked out of the display case during the release and before the door was opened. However, the impinged jet release at the bottom of the display case created a higher concentration cloud at the base of the display case that was released when the door was opened. The flame lasted for less than 1 second.



Refrigerant concentration until leak end



Pressure after ignitor first energized



Temperature after ignitor first energized

No measured increase.

Heat flux after ignitor first energized

Image 1

Image 2

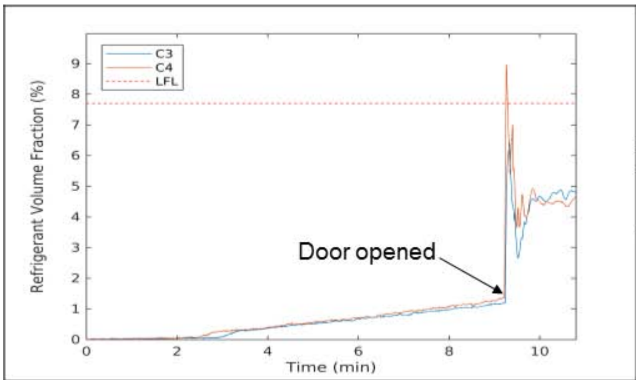
Figure 5.28: Data for Test #16.

Table 5.23: Test #17 conditions.

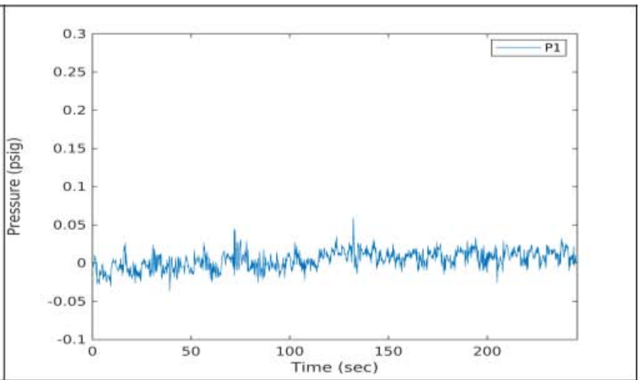
Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
17	R-454C	Inside	Free jet - vapor	200	1800	Off	0.0042

Ignition occurred in Test #17. The resulting flame movement during this test was different than seen in the external release tests with R-454C in that the flames were carried away from the ignitors and display case by the flow generated when the display case door was opened. In other words, the gas mixtures were not quiescent in this test when ignition occurred, as was the case for the tests with external releases, and this caused the flame to travel away from the ignitors. The flames lasted for approximately 2 seconds.

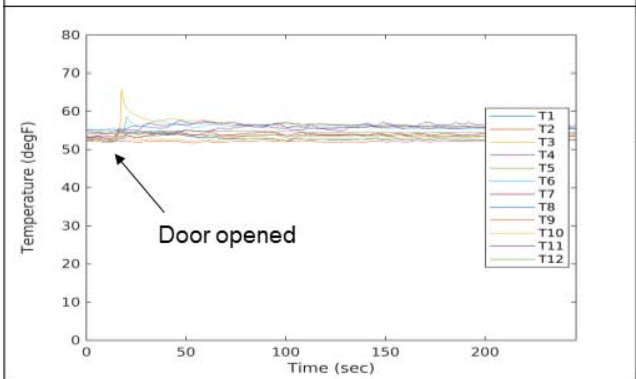
Refrigerant leaked out of the display case during the release and before the door was opened. If there was no leakage from the cabinet during the release and uniform mixing (via the free jet release), the concentration of R-454C in the cabin would have been approximately 10% by volume and close to stoichiometric. The actual concentration was lower due to the leakage.



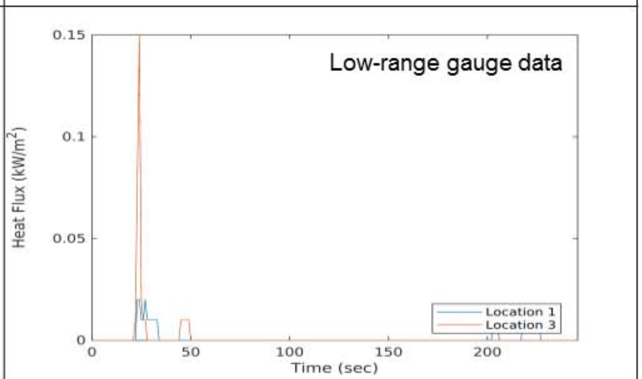
Refrigerant concentration until leak end



Pressure after ignitor first energized



Temperature after ignitor first energized



Heat flux after ignitor first energized

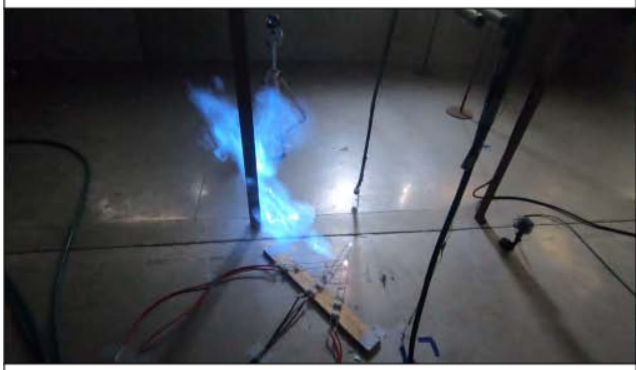


Image 1

Image 2

Figure 5.29: Data for Test #17.

Table 5.24: Test #18 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
18	R-454C	Inside	Impinged jet - vapor	200	1800	Off	0.0045

Ignition occurred in Test #18. Like in Test #17, flames were carried away from the ignitors and display case by the flow induced when the display case door was opened. As in the other internal release tests, R-454C leaked from the display case during the internal release. The flames lasted for approximately 2 seconds.

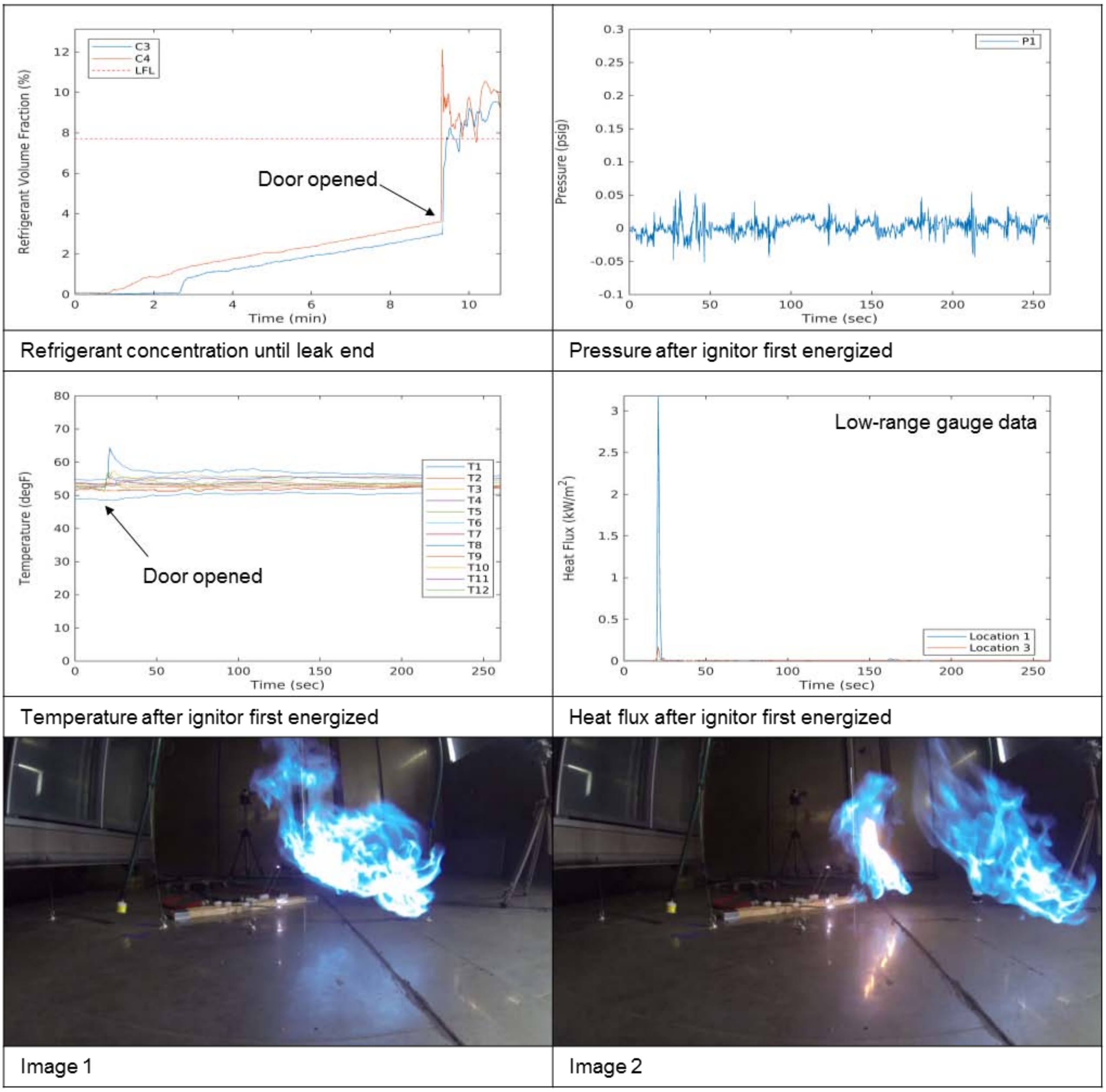


Figure 5.30: Data for Test #18.

Table 5.25: Test #19 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
19	R-454C	Inside	Free jet - vapor	200	1800	Off	0.0236

Test #19 was a repeat of Test #17, but in higher-humidity air. Ignition occurred in Test #19 and the fire size was considerably larger than in Test #17. Figure 5.32 shows the flame progression once ignited. Notice that approximately 7 seconds after ignition the flame is directly in front of the heat flux gauges at Location #1, and this is when we see the very short duration peak heat fluxes around 150 kW/m^2. While these values are on the order as those measured during the R-290 tests, the durations are much shorter, and the overall flame size is smaller throughout the post-ignition event. This means that, while the thermal exposure measured at location 1 is similar for a brief moment, thermal exposures at locations farther away from the ignition source are much lower compared to in the R-290 tests. This is evident by the very low heat flux measurement at Location #3.

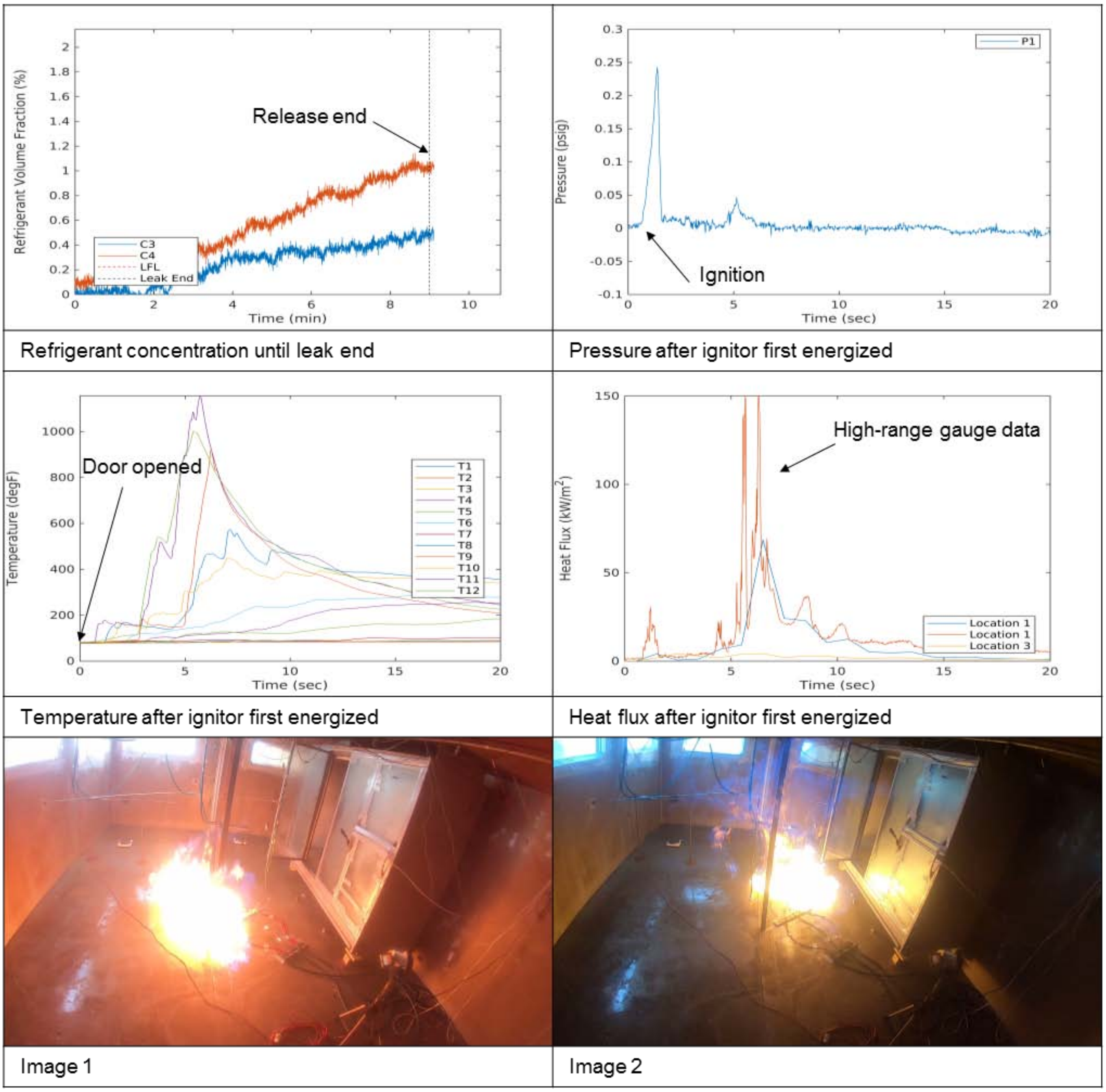


Figure 5.31: Data for Test #19.

Figure 5.32: Test #19 flame evolution after ignition.

Table 5.26: Test #20 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
20	R-290	Inside	Impinged jet - vapor	120	900	Off	< 0.0063

Ignition occurred in Test #20 when the ignitor was first energized and before the door was opened. Enough R-290 leaked out of the display case during the release that flammable concentrations existed at the ignitor when it was energized. When ignition occurred, a flame propagated into the display case and caused the door to open. Flames then extended out of the display case. The ignition event damaged the gas sensors and caused them to read 0% oxygen (i.e., 100% R-290).

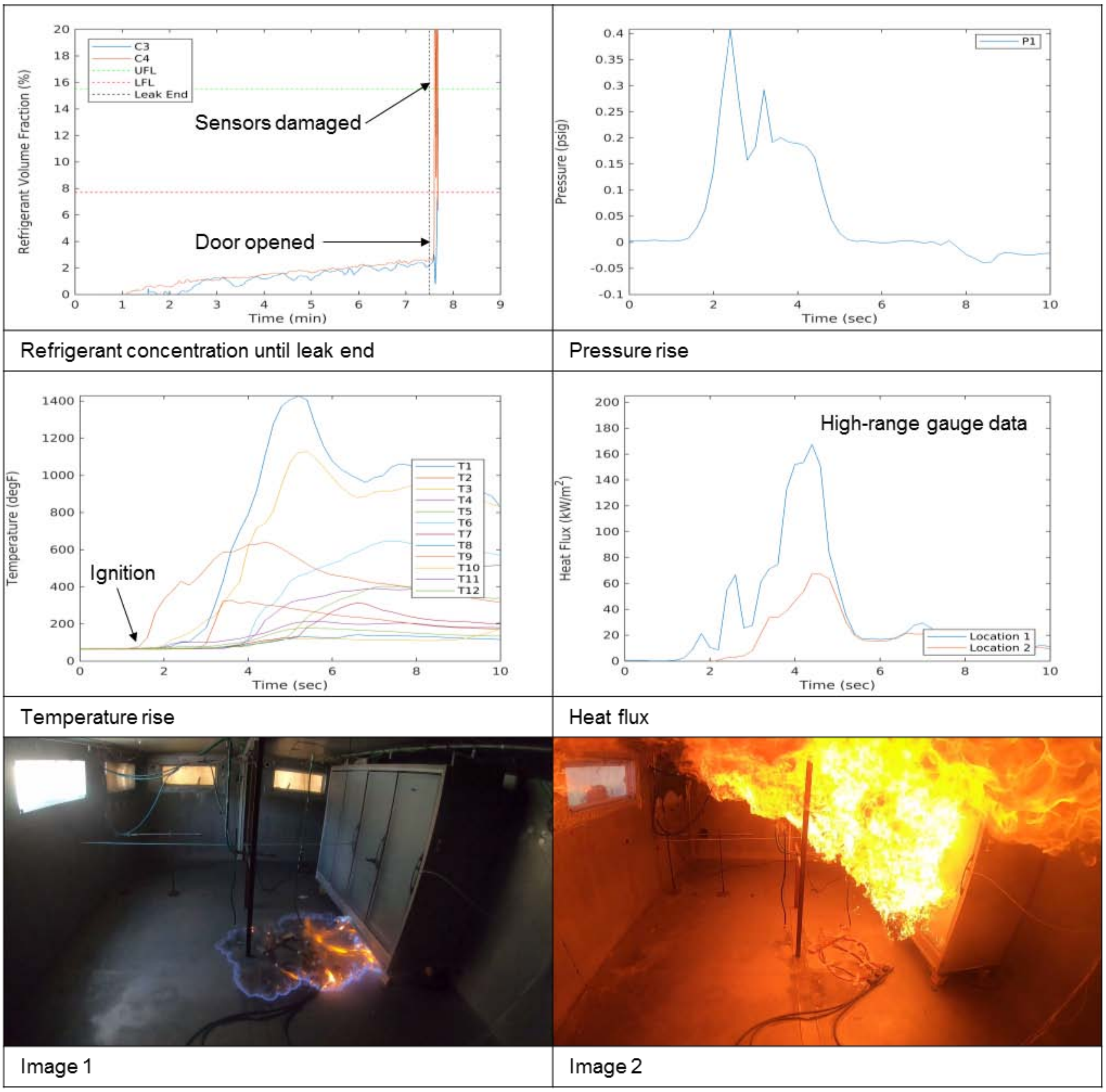


Figure 5.33: Data for Test #20.

Table 5.27: Test #21 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
21	R-290	Inside	Free jet - vapor	120	900	Off	< 0.0063

Ignition occurred in Test #21 after the display case door was opened. When ignition occurred, the flame propagated back into the display case. Flames then extended out of the display case. The ignition event damaged the gas sensors and caused them to read 0% oxygen (i.e., 100% R-290).

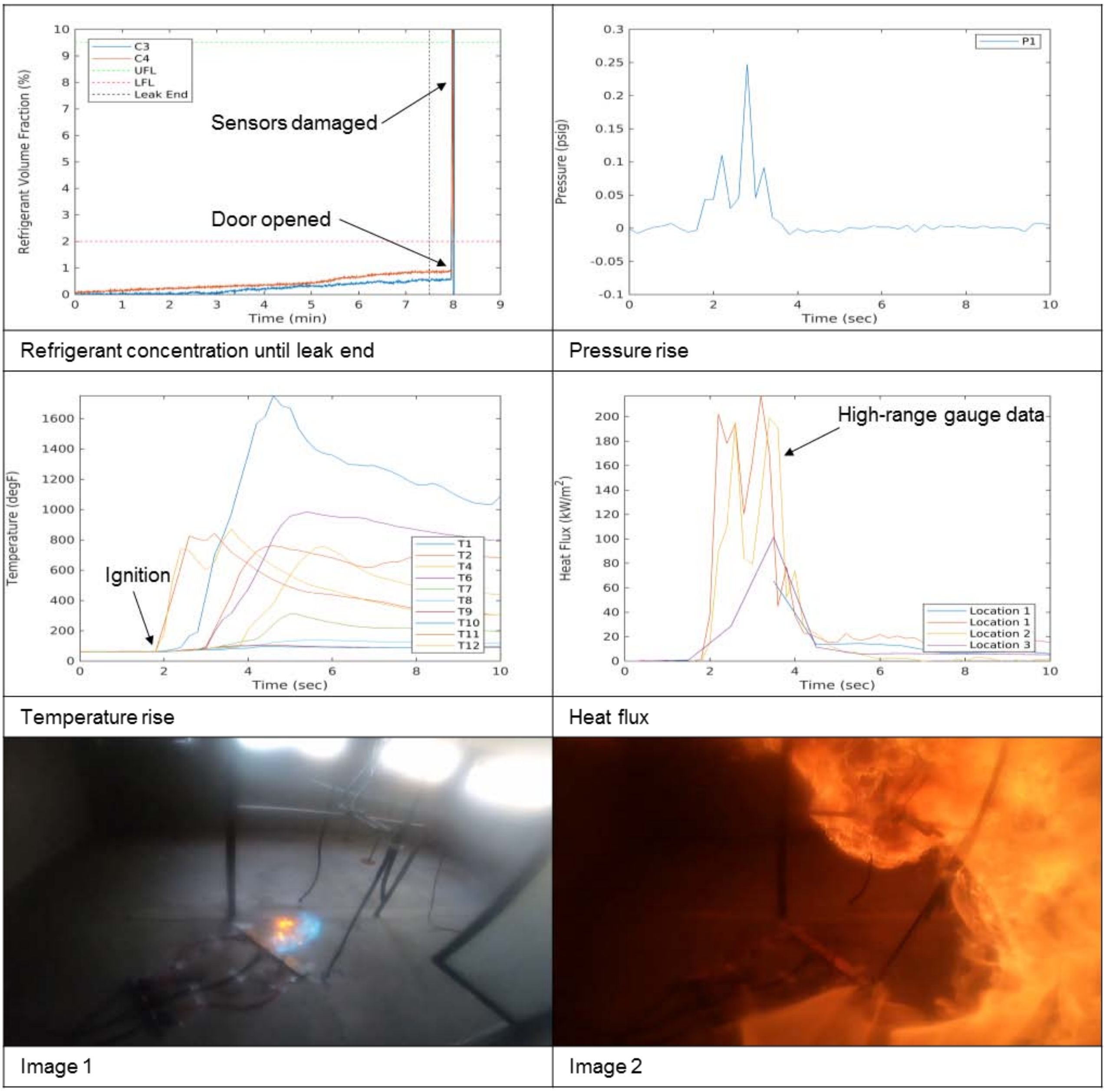


Figure 5.34: Data for Test #21.

Table 5.28: Test #22 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
22	R-454C	In Front	Free jet - vapor	550	1000	Off	< 0.0063

We performed Test # 22 three times with three different ignition source configurations and ignition never occurred.

Figure 5.35: Images during the vapor release for Test #22.

Table 5.29: Test #23 conditions.

Ignition test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)
23	R-454C	In Front	Free jet - liquid	4450	1000	Off	< 0.0063

We performed Test # 23 three times with three different ignition source configurations and ignition never occurred.

Figure 5.36 Images during the liquid release for Test #23.

5.5 Effectiveness of mitigation strategies during R-454C tests

Consequence mitigation strategies include limiting maximum allowable charge sizes, placing the condensing unit on the top of the display case, and either continuously operating the condensing fan or activating it when a refrigerant sensor detects a leak. This section discusses the effectiveness of these strategies when applied in the present study.

Limiting charge size

Table 5.30 lists three tests performed with the same conditions other than the amount of R-454C released. At the smallest release amount of 600 g, ignition did not occur. When releasing 1200 g and 2000 g, small to moderately sized flames anchored to the ignitors while they were energized. When the ignitors were turned off, the flames extinguished. While the ignition consequences were minor when releasing 1200 g and 2000 g, reducing the amount released to 600 g prevented ignition altogether.

Table 5.30: Sensitivity to released amount.

Ignition test #	Dispersion test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)	Result
2	34	R-454C	Bottom	Impinged jet - vapor	200	600	Off	< 0.0063	1
3	35	R-454C	Bottom	Impinged jet - vapor	200	1200	Off	< 0.0063	2
4	36	R-454C	Bottom	Impinged jet - vapor	200	2000	Off	< 0.0063	3

Results key

1 - No ignition

2 - Ignition with small flames anchored to the ignitors which extinguished when ignitors were turned off

3 - Ignition with moderately sized flames anchored to ignitors which extinguished when ignitors were turned off

Condensing unit location

Table 5.31 shows two similar R-454C tests but with the release occurring below and above the display case. Concentrations remained well below the LFL at the concentration sensors (i.e., a maximum of 1.5% by volume) during Test #9 with a top release and thus ignition was prevented. The released refrigerant was able to mix more thoroughly with air as it cascaded downward towards the floor as a result of it being more dense than air.

Table 5.31: Sensitivity to condensing unit location.

Ignition test #	Dispersion test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)	Result
4	36	R-454C	Bottom	Impinged jet - vapor	200	2000	Off	< 0.0063	3
9	12	R-454C	Top	Impinged jet - vapor	200	2000	Off	< 0.0063	1

Results key

1 - No ignition

2 - Ignition with small flames anchored to the ignitors which extinguished when ignitors were turned off

3 - Ignition with moderately sized flames anchored to ignitors which extinguished when ignitors were turned off

Condenser fan operation during the release

Table 5.32 shows two similar R-454C tests with the mock-up condensing unit fan off and on. Concentrations remained well below the LFL at the concentration sensors (i.e., a maximum of 1.2% by volume) during Test #6 with the condenser fan on. The flow velocities induced by the fan mixed the released refrigerant more thoroughly with the air in the test room and therefore prevented higher concentrations from forming at the floor.

Table 5.32: Sensitivity to condenser fan operation.

Ignition test #	Dispersion test #	Refrigerant	Release location	Release type	Leak rate (g/min)	Charge size (g)	Condenser fan (off/on)	Absolute humidity (g-H2O/g-air)	Result
3	35	R-454C	Bottom	Impinged jet - vapor	200	1200	Off	< 0.0063	2
6	39	R-454C	Bottom	Impinged jet - vapor	200	1200	On	< 0.0063	1

Results key

1 - No ignition

2 - Ignition with small flames anchored to the ignitors which extinguished when ignitors were turned off

5.6 R-454C vs. R-290

This section compares the ignition events during tests with equivalent R-454C and R-290 releases.

Table 5.33 shows the equivalent test comparisons that can be made using the data from this study as well as data from the final report from the FPRF R-290 study [2].

Table 5.33: Summary of available comparisons

Comparison #	Release Location	Release type	Condenser Fan (Off/On)	R290		R454C	
				Charge Size (g)	Leak Rate (g/min)	Charge Size (g)	Leak Rate (g/min)
1	Bottom	Impinged jet - vapor	Off	300	335	600	550
2	Bottom	Impinged jet - vapor	Off	600	12	1200	20
3	Bottom	Impinged jet - vapor	Off	600	120	1200	200
4	Bottom	Impinged jet - vapor	On	600	120	1200	200
5	Bottom	Impinged jet - vapor	Off	1000	120	2000	200
6	Top	Impinged jet - vapor	Off	1000	120	2000	200
7	Inside	Free jet - vapor	-	900	120	1800	200
8	Inside	Impinged jet - vapor	-	900	120	1800	200
9	In Front	Free jet - vapor	-	-	380	-	550
10	In Front	Free jet - liquid	-	-	3050	-	4450

Table 5.34: Test conditions for Comparison #1.

Comparison #	Release Location	Release type	Condenser Fan (Off/On)	R290		R454C	
				Charge Size (g)	Leak Rate (g/min)	Charge Size (g)	Leak Rate (g/min)
1	Bottom	Impinged jet - vapor	Off	300	335	600	550

Comparison #1 involves Test #7 and #11 from this study. In Test #7 with R-454C, ignition occurred with small flames anchored to the ignitors that extinguished when the ignitors were turned off. In Test #11 with R-290, ignition occurred, and flames propagated throughout the room.

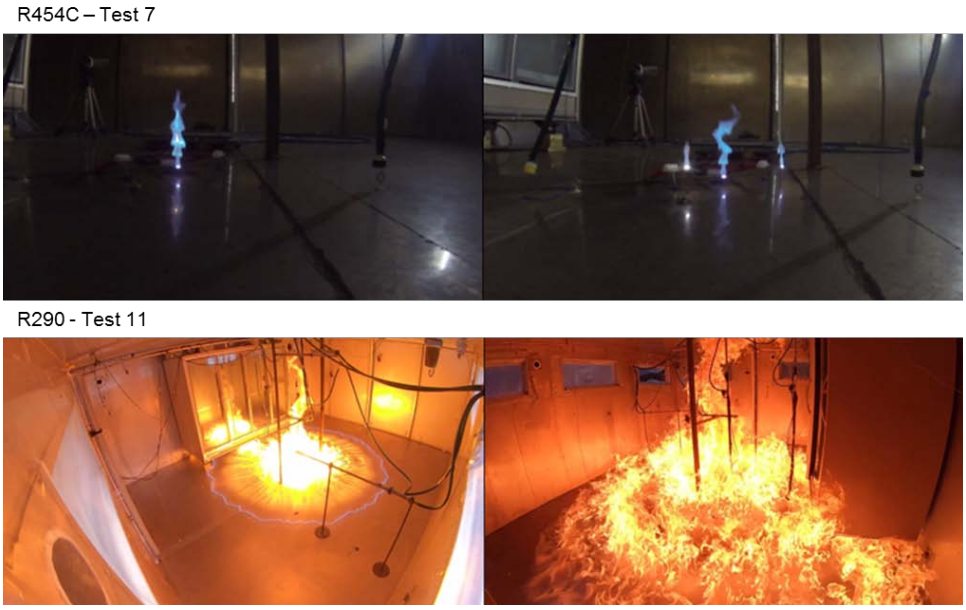


Figure 5.37: R-454C vs R-290 test comparison #1.

Table 5.35: Test conditions for Comparison #2.

Comparison #	Release Location	Release type	Condenser Fan (Off/On)	R290		R454C	
				Charge Size (g)	Leak Rate (g/min)	Charge Size (g)	Leak Rate (g/min)
2	Bottom	Impinged jet - vapor	Off	600	12	1200	20

Comparison #2 involved Test #1 from this study and Test #2 from the FPRF R-290 study. In Test #1 with R-454C, ignition did not occur. In Test #2 from the FPRF R-290 study, ignition occurred, and flames propagated across the floor and burned in front of the display case.

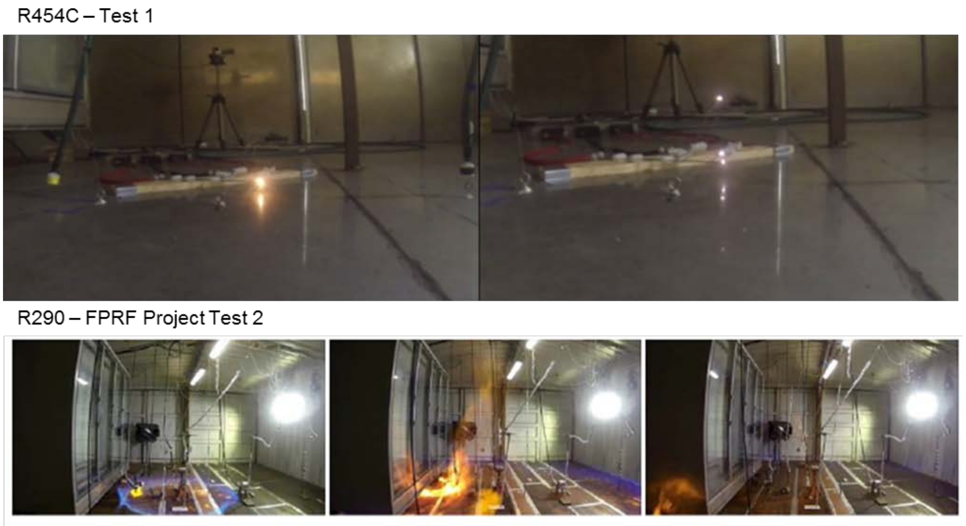


Figure 5.38: R-454C vs R-290 test comparison #2.

Table 5.36: Test conditions for Comparison #3.

Comparison #	Release Location	Release type	Condenser Fan (Off/On)	R290		R454C	
				Charge Size (g)	Leak Rate (g/min)	Charge Size (g)	Leak Rate (g/min)
3	Bottom	Impinged jet - vapor	Off	600	120	1200	200

Comparison #3 involved Test #3 and #13 from this study. In Test #3 with R-454C, ignition occurred, and small flames remained anchored to the ignitors which extinguished when ignitors were turned off. In Test #13 with R-290, ignition occurred, and flames propagated throughout the room and lasted for approximately 4-5 seconds.

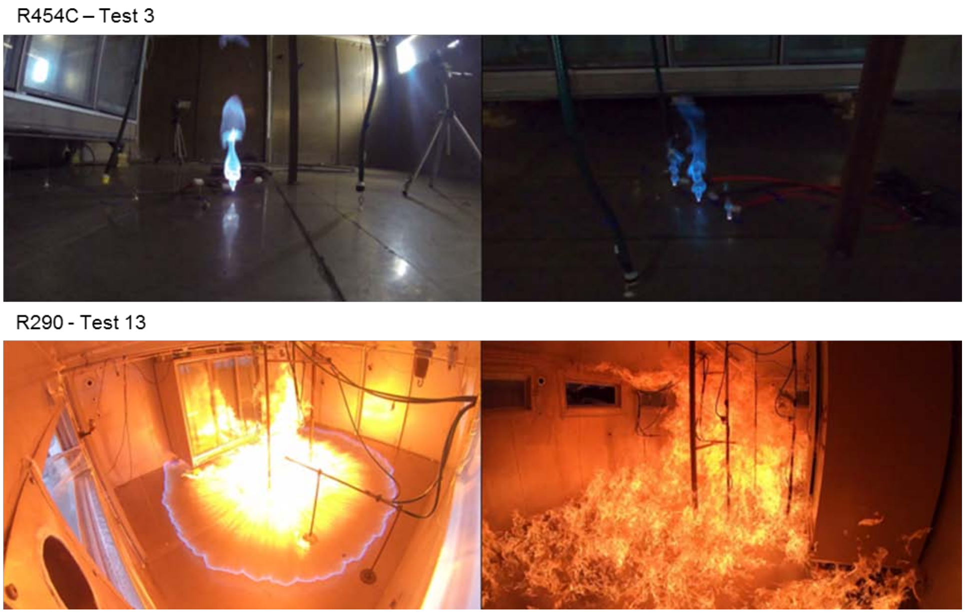


Figure 5.39: R-454C vs R-290 test comparison #3.

Table 5.37: Test conditions for Comparison #4.

Comparison #	Release Location	Release type	Condenser Fan (Off/On)	R290		R454C	
				Charge Size (g)	Leak Rate (g/min)	Charge Size (g)	Leak Rate (g/min)
4	Bottom	Impinged jet - vapor	Off	600	335	1200	550

Comparison #4 involves Tests #8 and #12 from this study. In Test #8 with R-454C, ignition occurred, and small flames remained anchored to the ignitors which extinguished when ignitors were turned off. In Test #12 with R-290, ignition occurred, and flames propagated throughout the room and lasted for approximately 4-5 seconds.

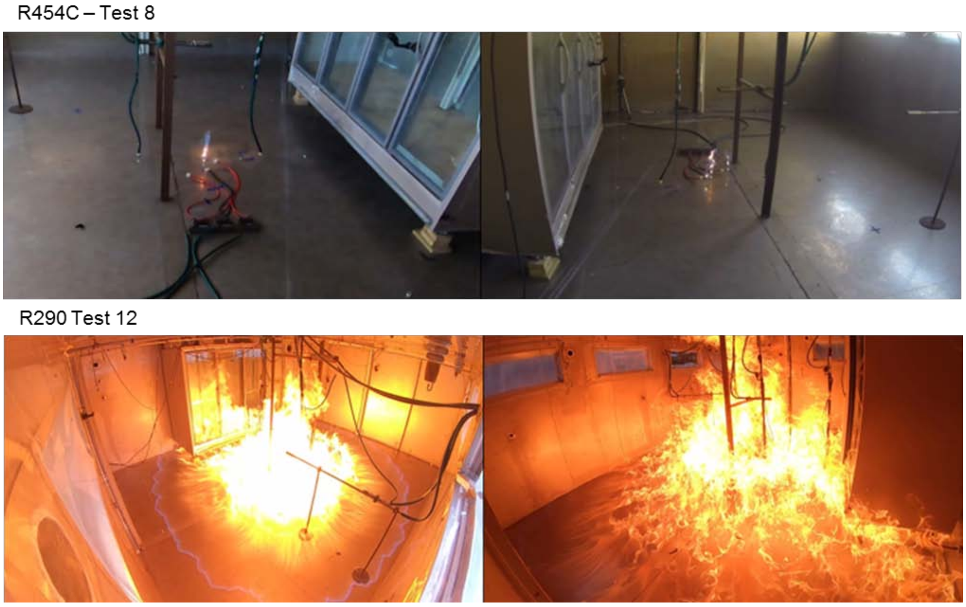


Figure 5.40: R-454C vs R-290 test comparison #4.

Table 5.38: Test conditions for Comparison #5.

Comparison #	Release Location	Release type	Condenser Fan (Off/On)	R290		R454C	
				Charge Size (g)	Leak Rate (g/min)	Charge Size (g)	Leak Rate (g/min)
5	Bottom	Impinged jet - vapor	Off	1000	120	2000	200

Comparison #5 involves Test #5 from this study and Test #6 from the FPRF R-290 study. Test #5 was the test performed with higher-humidity air and was selected for this comparison because it shows the more severe consequence out of the two equivalent R-454C tests done in low-humidity and higher-humidity air. In Test #5 with R-454C, ignition occurred, and a flame initially remained stationary at the ignitor location for the first 30 seconds while the ignitor was still energized. When the ignitor was turned off, the flames slowly spread radially and downward until they contacted the equipment and cabling along the ground. During the most intense burning, the flame height reached approximately 3 feet (1 m) and the flames lasted for approximately 110 seconds. In Test #6 from the FPRF R-290 study, ignition occurred, and flames propagated throughout the room.

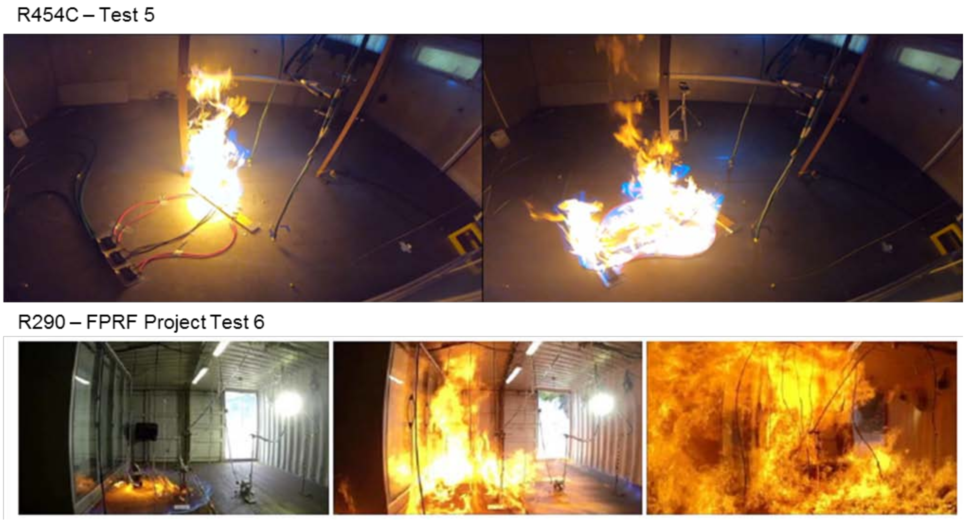


Figure 5.41: R-454C vs R-290 test comparison #5.

Table 5.39: Test conditions for Comparison #6.

Comparison #	Release Location	Release type	Condenser Fan (Off/On)	R290		R454C	
				Charge Size (g)	Leak Rate (g/min)	Charge Size (g)	Leak Rate (g/min)
6	Top	Impinged jet - vapor	Off	1000	120	2000	200

Comparison #6 involves Test #9 from this study and Test #12 from the PFRF R-290 study. In Test #9, ignition did not occur because concentrations remained well below the LFL throughout the test room and at the ignitor locations. In Test #12 from the FPRF R-290 study, ignition occurred, and flames propagated throughout the room in a more premixed fashion, hence the predominantly blue flames as opposed to yellow flames. This is because both refrigerants mixed with a larger volume of air in the room when released from the top of the display case, hence resulting in R-454C concentrations below the LFL and R-290 more uniformly mixed with air, but still within the flammability limits.

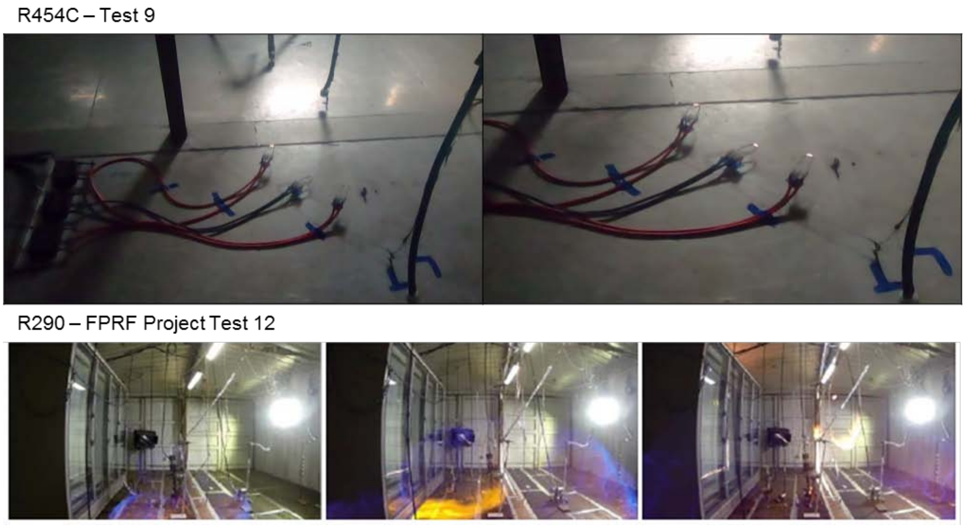


Figure 5.42: R-454C vs R-290 test comparison #6.

Table 5.40: Test conditions for Comparison #7.

Comparison #	Release Location	Release type	Condenser Fan (Off/On)	R290		R454C	
				Charge Size (g)	Leak Rate (g/min)	Charge Size (g)	Leak Rate (g/min)
7	Inside	Free jet - vapor	-	900	120	1800	200

Comparison #7 involves Test #19 from this study and Test #14 from the FPRF R-290 study. Test #19 was the test performed in higher-humidity air and was selected for this comparison because it shows the more severe consequence out of the two equivalent R-454C tests done in low-humidity and higher-humidity air. In Test #19 with R-454C, ignition occurred, and a moderately-sized fireball burned in front of the display case for approximately 7 seconds before propagating into the display case where it continued to burn at a smaller size for another 10 seconds. In Test #14 from the FPRF R-290 study, ignition occurred, and flames propagated into the display case and burned in front of it. The fireball was at least a factor of two larger than in the test with R-454C.

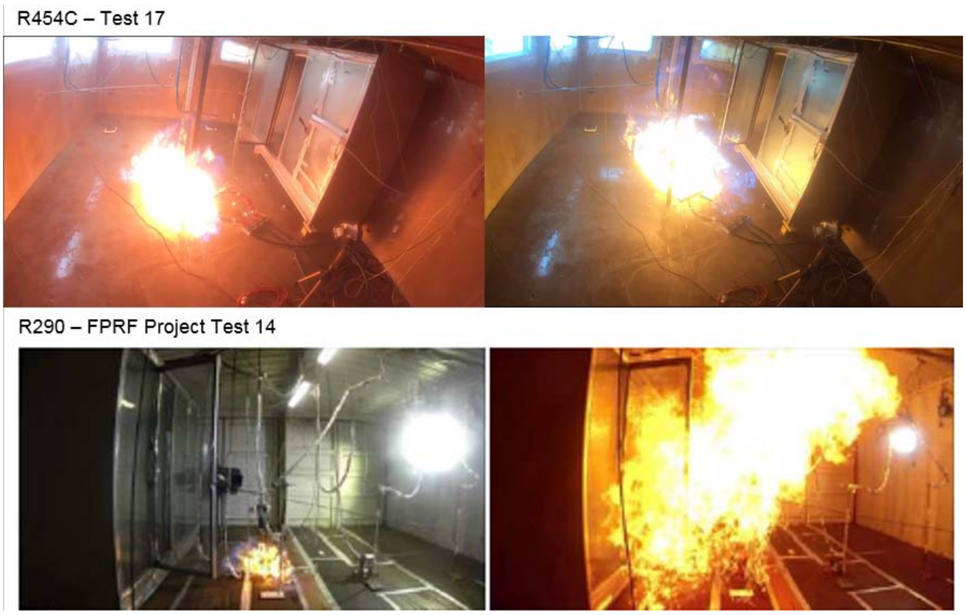


Figure 5.43: R-454C vs R-290 test comparison #7.

Table 5.41: Test conditions for Comparison #8.

Comparison #	Release Location	Release type	Condenser Fan (Off/On)	R290		R454C	
				Charge Size (g)	Leak Rate (g/min)	Charge Size (g)	Leak Rate (g/min)
8	Inside	Impinged jet - vapor	-	900	120	1800	200

Comparison #8 involves Tests #18 and #20 from this study. In Test #18 with R-454C, ignition occurred, and flames extended away from the display case and burned for about 2 seconds. In Test #20 with R-290, ignition occurred before the display case door was opened. Flames traveled into the display case and caused the door to open. Flames then extended out of the display case and burned in front of it.

R454C – Test 18

R290 –Test 20

Figure 5.44: R-454C vs R-290 test comparison #8.

Table 5.42: Test conditions for Comparison #9.

Comparison #	Release Location	Release type	Condenser Fan (Off/On)	R290		R454C	
				Charge Size (g)	Leak Rate (g/min)	Charge Size (g)	Leak Rate (g/min)
9	In Front	Free jet - vapor	-	-	380	-	550

Comparison #9 involves Test #22 from this study and Test #15 from the FPRF R-290 study. The free jet vapor release with R-454C did not ignite whereas the R-290 release did, creating a jet flame approximately 2 ft in length when the ignition source was present and extinguished when the ignition source was removed.

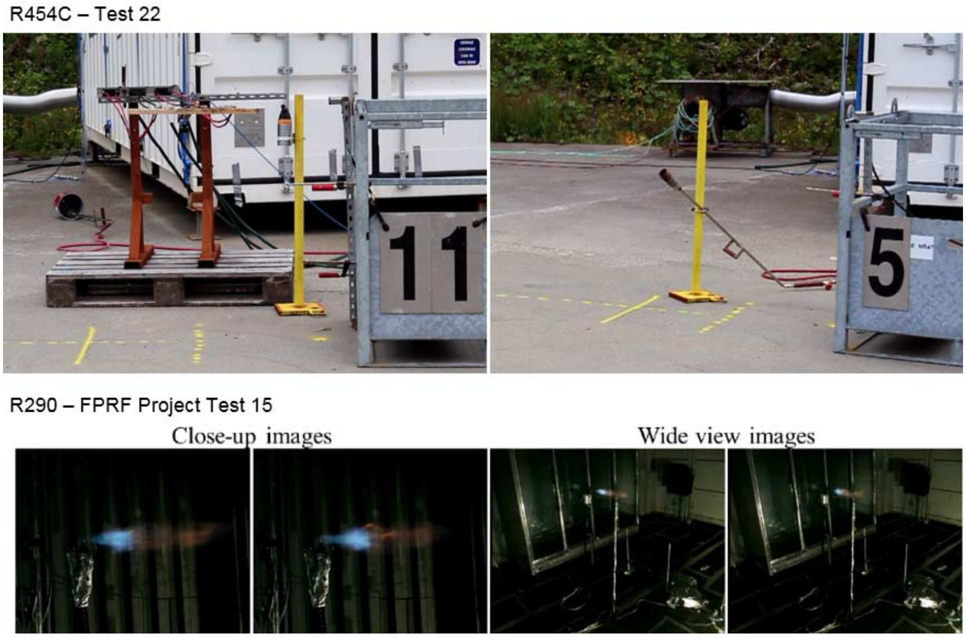


Figure 5.45: R-454C vs R-290 test comparison #9.

Table 5.43: Test conditions for Comparison #10.

Comparison #	Release Location	Release type	Condenser Fan (Off/On)	R290		R454C	
				Charge Size (g)	Leak Rate (g/min)	Charge Size (g)	Leak Rate (g/min)
10	In Front	Free jet - liquid	-	-	3050	-	4450

Comparison #9 involves Test #23 from this study and Test #16 from the FPRF R-290 study. The free jet liquid release with R-454C did not ignite whereas the R-290 release did, creating a sustained jet flame approximately 6 ft in length.

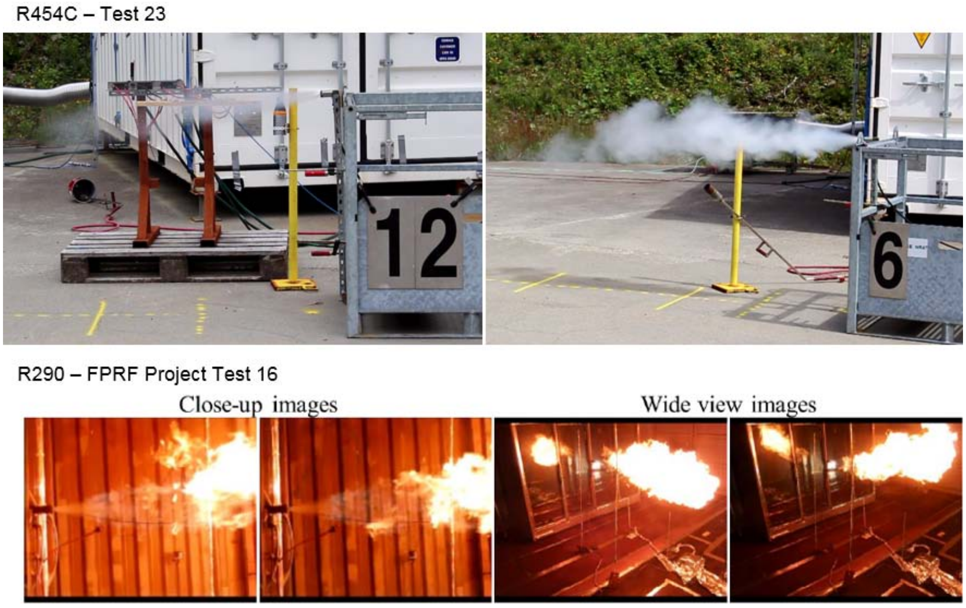


Figure 5.46: R-454C vs R-290 test comparison #10.

5.7 Comparisons with reach-in cooler tests from AHRTI 9007 project

The AHRTI 9007 project aimed to experimentally evaluate the ignition consequences of room-scale ignition events involving A2L refrigerants and was completed in 2017 [9]. In four of the AHRTI 9007 tests, A2L refrigerants were released inside a closed reach-in cooler (i.e., a refrigerated display case) and then the cooler door was opened with several live ignition sources in the room. Hence, these tests were similar to the in-cabinet release tests performed in the present study. One of the tests from AHRTI 9007 (labeled Cooler01 in the final report) involved a 500 g release of R-455A with the air in the room conditioned to 32 °C and 70% RH (absolute humidity of 0.0222 g-H2O / g-dry-air). Figure 5.47 compares the ignition event from this test to the ignition event during Test #19 of the present study which involved a 1000 g release of R-454C inside the display case with the air in the room pre-conditioned to 27 °C and 100% RH (absolute humidity of 0.0236 g-H_2O / g-air). The outcomes of these two tests are compared because R-454C and R-455A both have a peak laminar burning velocity of approximately 5 cm/s in air at these absolute humidity levels.[3]

As the images in Figure 5.47 show, the ignition events during the two tests were very similar. The maximum fire size and fire duration was similar in both tests and the fires moved across the floor and in front of the display cases at similar speeds. Note that in the AHRTI 9007 test, the flames extended farther upward because there were cheesecloth strands hanging from the ceiling.

[3] Unpublished experimental result recently obtained by Gexcon as part of the ASHRAE 1806 project that is still underway.

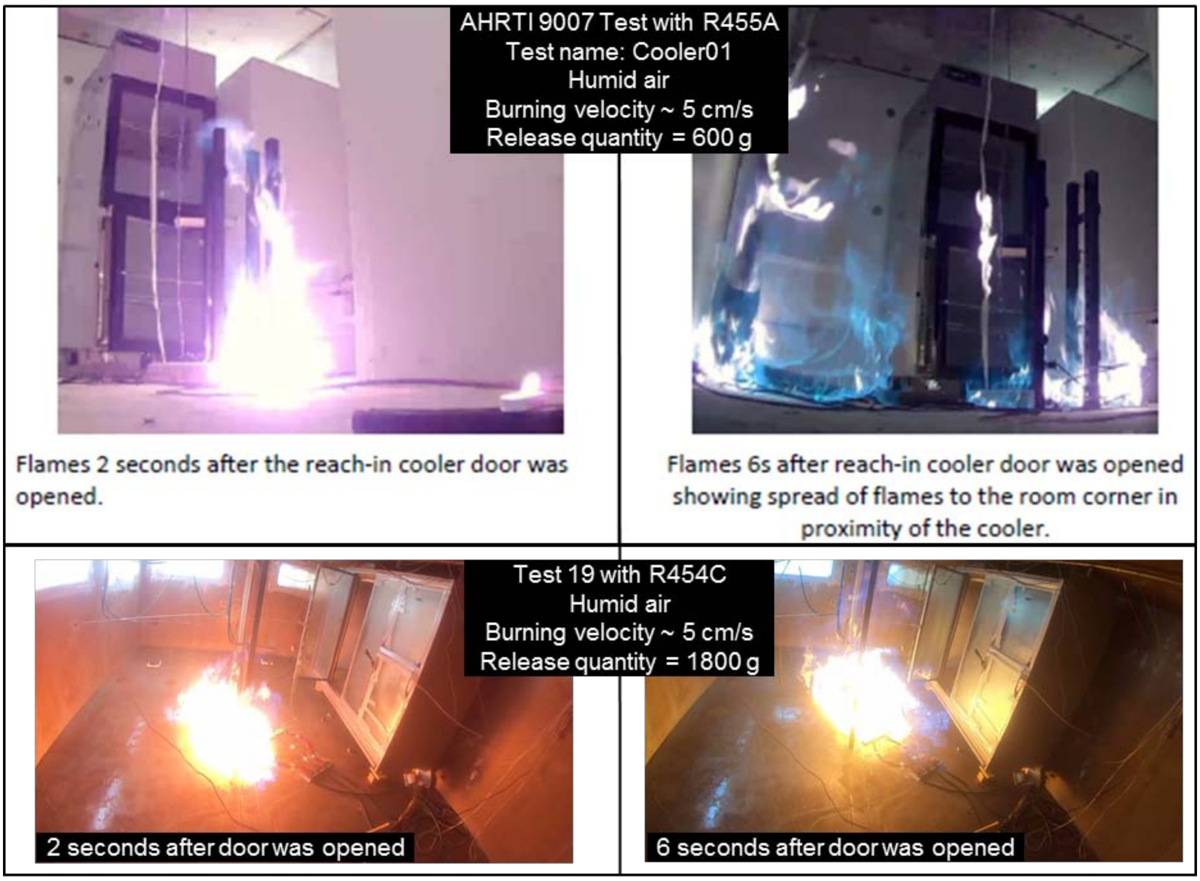


Figure 5.47: Comparison of ignition events in a reach-in cooler test from the present study (Test #19) and from AHRTI 9007 (Cooler01). Both tests performed with elevated humidity and a resulting refrigerant/air mixture peak laminar burning velocity of approximately 5 cm/s.

6 Conclusions

The majority of tests with R-454C in low-humidity air either did not ignite or produced small stationary flames anchored to the ignitors that extinguished when the ignitors were turned off. The two R-454C tests that created the largest flames were repeated with higher-humidity air in the test enclosure: one test involved an impinged release in a bottom mounted condensing unit and the other a release inside the conditioned space of the display case. In the higher-humidity test with the release in the condensing unit, the resulting fire was somewhat larger, but still contained within a few-foot radius of the ignitor. When the ignitor was turned off, the fire continued to burn in a pool-fire fashion for about 1.5 minutes. In the in-cabinet R-454C release test with higher-humidity, the fire was larger, more vigorous, and shorter in duration; with the increased reactivity likely due to the flow-induced turbulence created by the refrigerant/air mixture as it exited the display once the door was opened. The outcome of this test was similar to what was observed in the reach-in cooler tests performed as part of AHRTI 9007. For the R-290 release tests, ignition event involved much larger fires that spread across the floor and in some cases throughout the room. With R-290, the fires lasted anywhere from 2 seconds to 5 seconds depending on the amount of R-290 released.

Test results from this study and from the FPRF R-290 study enabled ignition consequence comparisons for ten equivalent release scenarios with R-290 and R-454C in dry air. In four of the ten scenarios, the R-290 releases created severe ignition events and R-454C releases resulted in no ignition. In the other six scenarios, the R-290 releases once again created severe ignition events and R-454C releases resulted in small, minimal consequence flames at the ignitors that extinguished when the ignitors were turned off. The two R-454C releases repeated with higher humidity air resulted in larger, higher consequence flames which continued to burn in the absence of a live ignition source. While the ignition events were more severe in humid air, they were still much less severe than the equivalent release scenarios with R-290, whereby the overall fire sizes were still smaller and therefore the heat flux and overpressure hazards were lower.

When releasing “equivalent volume” charge sizes through equivalent leak hole sizes, R-290 ignition events were much more severe for the following reasons: (1) the LFL of R-290 is lower and therefore some of the equivalent releases produced flammable concentrations with R-290 and not with R-454C; and (2) R-290 is much more reactive than R-454C and thus flames could more quickly propagate away from the ignition location to other areas of the room where flammable concentrations existed regardless of the humidity conditions and turbulence at the time of ignition. Ignition events with layered fuel clouds containing R-290 resulted in much larger, shorter duration fires with much higher heat flux and pressure rise potential. This was not the case for layered fuel clouds containing R-454C, which under low-humidity conditions, could not maintain a flame after the ignitors were turned off. When the reactivity was increased by increasing the humidity in the test enclosure, the resulting fire was still smaller and of longer duration compared to R-290. Only once the reactivity was increased both due to higher-humidity and flow-induced turbulence was there a higher consequence ignition event; however, the heat flux and overpressure hazards were still lower compared to tests with R-290 because the overall fire size and combustion severity remained smaller.

The testing showed that for the A2L refrigerant R-454C, the resulting ignition consequences were very minor under quiescent and low humidity conditions, and in fact combustion could only be maintained when the ignition source remained active. Based on these results, it is anticipated that the ignition consequences of other A2L refrigerants with burning velocities below 2 cm/s will also be very minor. In contrast, high consequence events were observed for R-290 under quiescent and low humidity conditions. In order to establish R-454C flames that could propagate away from the ignition source, higher humidity levels were required in order to increase the refrigerants reactivity (i.e., the burning velocity approached 5 cm/s). Higher consequence events did not occur with R-454C until both the humidity was increased (increase in the A2L’s reactivity) and flow induced turbulence was provided to increase the flame speed, resulting in more vigorously burning flames. However, when releasing 1800 g of R-454C under high-humidity and turbulent conditions, the fire size and radiative heat flux were similar to when releasing 150 g of R-290 at 120 g/min below the display case, which was our highest consequence event for R-290 utilizing the current charge limit in UL 60335-2-89 for commercial refrigeration applications.

This study also showed that equivalent releases of R-454C are less likely to result in ignition events altogether because the flammability range is narrower and therefore the flammable layer is typically narrower than during equivalent releases with R-290. With R-454C, it is therefore less likely that an ignition source would be present in the flammable layer because the layer is smaller.

This study did not quantify the levels of hydrogen fluoride in the test room, which is another potentially hazardous consequence of R-454C ignition events, and all ignition events with fluorinated compounds. While this study did not quantify the levels of hydrogen fluoride in the test room during and after ignition events, qualitative measurements were made within the test room with a 0-10 ppm sensor. For the minor ignition events, HF levels never exceeded 3 ppm and went off range (> 10 ppm) during the higher-consequence tests with high humidity and turbulence. Quantifying HF levels should be a topic of future work to further understand the consequences of ignition events involving fluorinated refrigerants.

References

1. McLinden, M.O., et al., *Limited options for low-global-warming-potential refrigerants.* Nature Communications, 2017. **8**.
2. Davis, S.G., *Evaluation of the Fire Hazard of ASHRAE Class A3 Refrigerants in Commercial Refrigeration Applications*. 2017.
3. Colbourne, D. and K. Suen. *R-290 Concentration arising from leaks in commercial refrigeration cabinets*. in *Gustav Lorentzen Natural Working Fluids Conference*. 2016. Edinburgh.
4. Takizawa, K., *Flammability Assessment of CH2= CFCF3 (R-1234yf) and its Mixtures with CH2F2 (R-32); 2010 International Symposium on Next-generation Air Conditioning and Refrigeration Technology.* Tokyo, JP, 2010: p. 1-8.
5. Vagelopoulos, C.M. and F.N. Egolfopoulos, *Direct Experimental Determination of Laminar Flame Speeds.* Twenty-Seventh Symposium on Combustion, 1998(513-519).
6. *Risk Assessment of Mildly Flammable Refrigerants - 2016 Final Report, Prepared for the Japanese Society of Refrigerating and Air Conditioning Engineers (JSRAE)*. 2017.

7. Colbourne, D. and K. Suen, *Appraising the flammability hazards of hydrocarbon refrigerants using quantitative risk assessment model. Part II. Model evaluation and analysis.* International journal of refrigeration, 2004. **27**(7): p. 784-793.
8. Colbourne, D. and L. Espersen, *Quantitative risk assessment of R-290 in ice cream cabinets.* International Journal of Refrigeration, 2013. **36**(4): p. 1208-1219.
9. Gandhi, P., G. Hunter, and R. Haseman, *Benchmarking Risk by Whole Room Scale Leaks and Ignitions Testing of A2L Refrigerants*. 2017, AHRTI 9007.

Appendix A – Dispersion Test Results

Provided below are the measured R-454C concentrations during the dispersion tests. Refer to Table 4.5 and Table 4.6 for the conditions of each test.

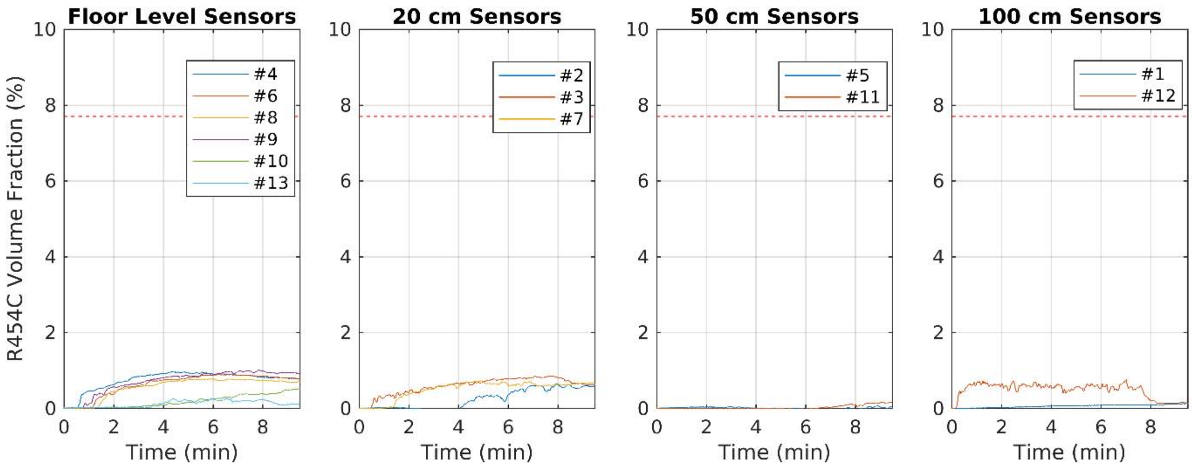


Figure A.1: Dispersion test #1 – top release, 20 g/min, condenser fan off, 150 g charge.

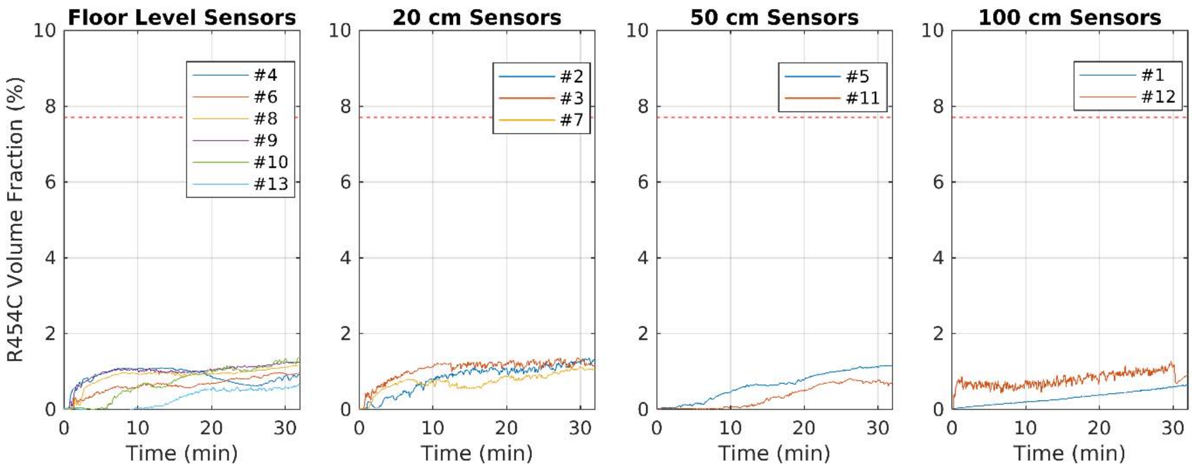


Figure A.2: Dispersion test #2 – top release, 20 g/min, condenser fan off, 600 g charge.

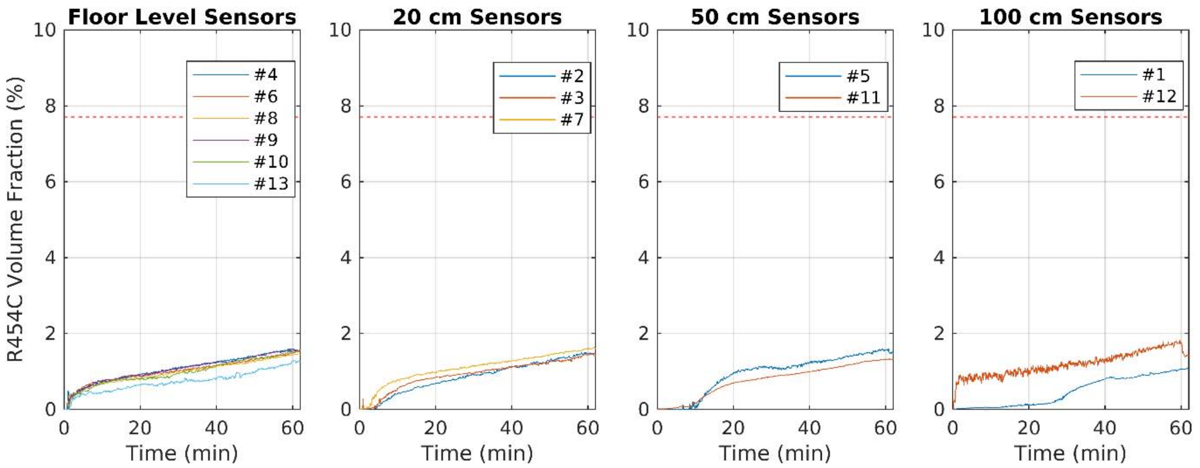


Figure A.3: Dispersion test #3 – top release, 20 g/min, condenser fan off, 1200 g charge.

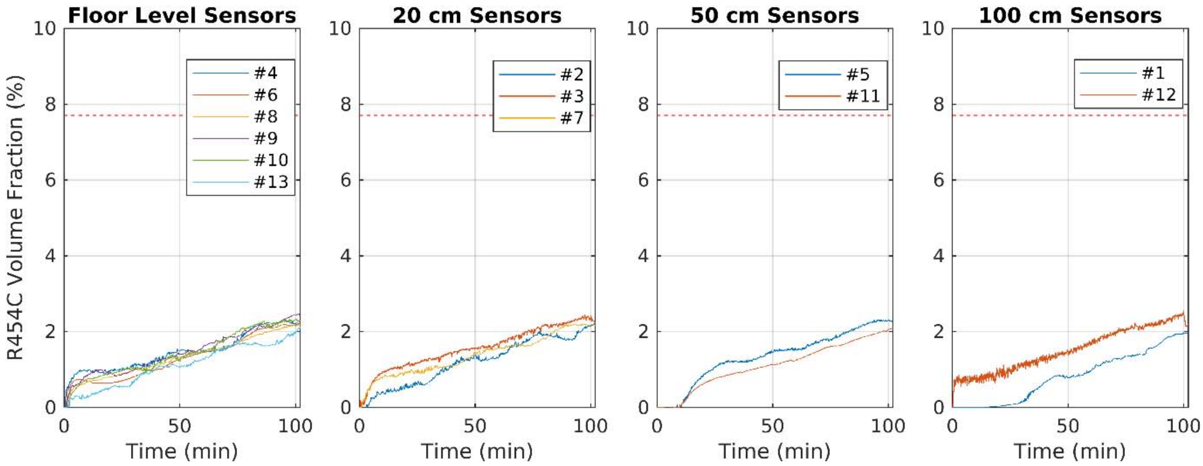


Figure A.4: Dispersion test #4 – top release, 20 g/min, condenser fan off, 2000 g charge.

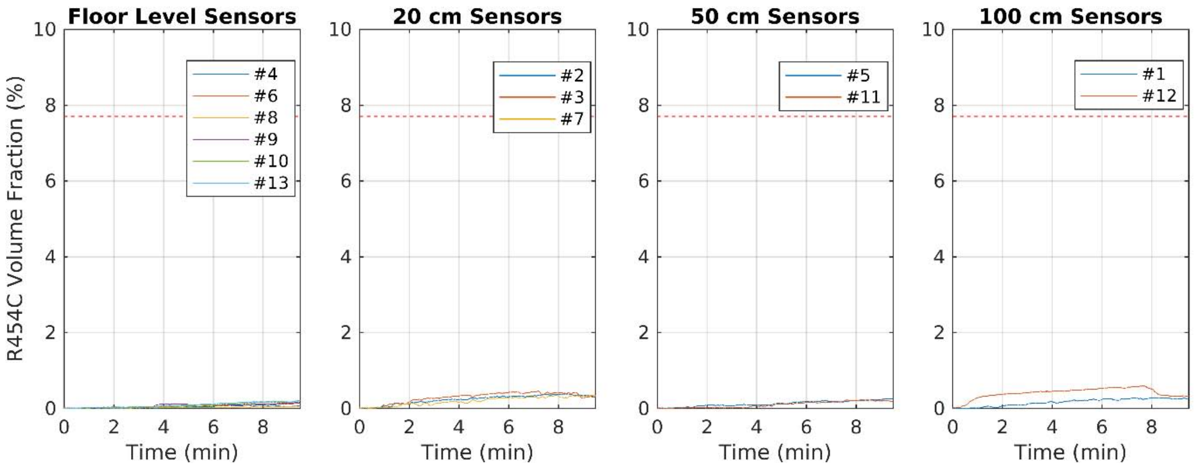


Figure A.5: Dispersion test #5 – top release, 20 g/min, condenser fan on, 150 g charge.

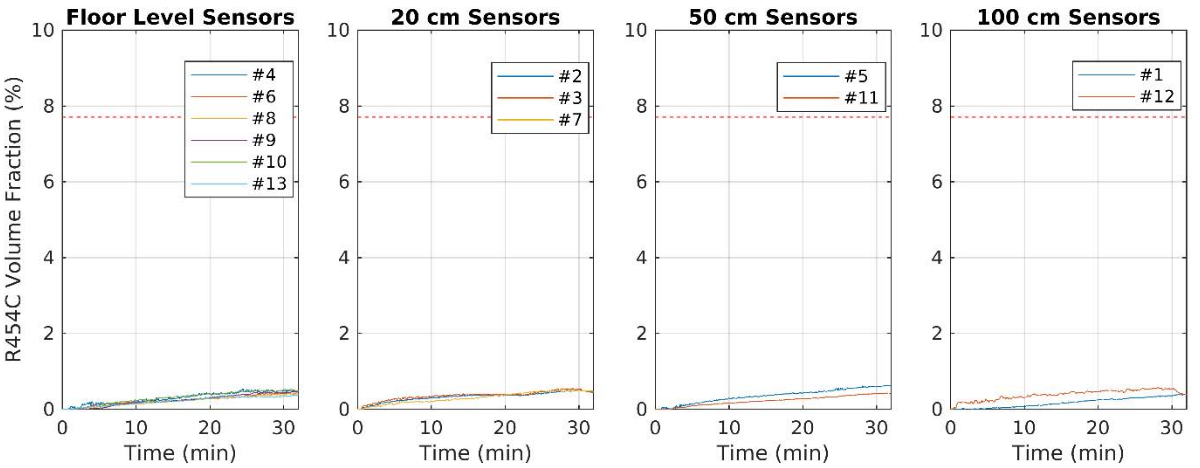


Figure A.6: Dispersion test #6 – top release, 20 g/min, condenser fan on, 600 g charge.

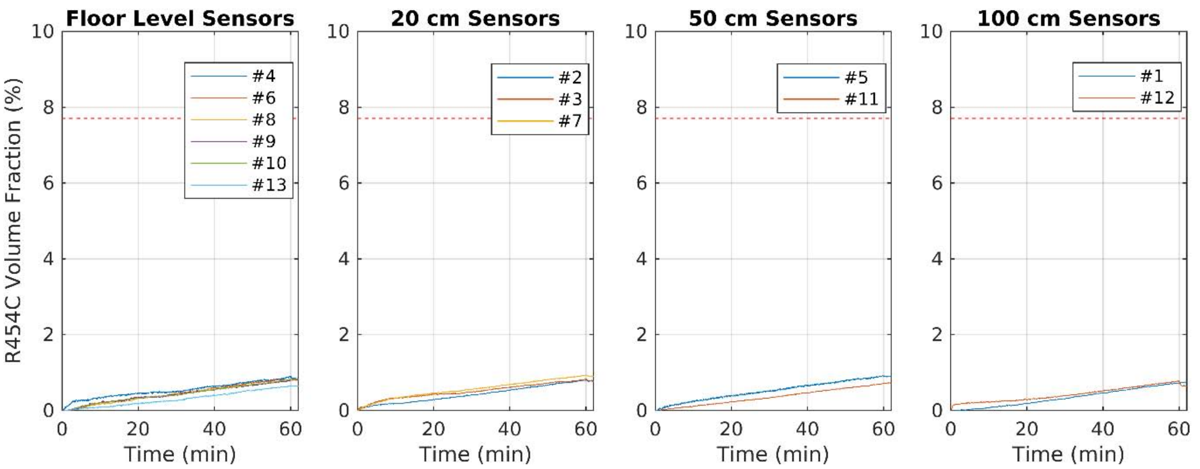


Figure A.7: Dispersion test #7 – top release, 20 g/min, condenser fan on, 1200 g charge.

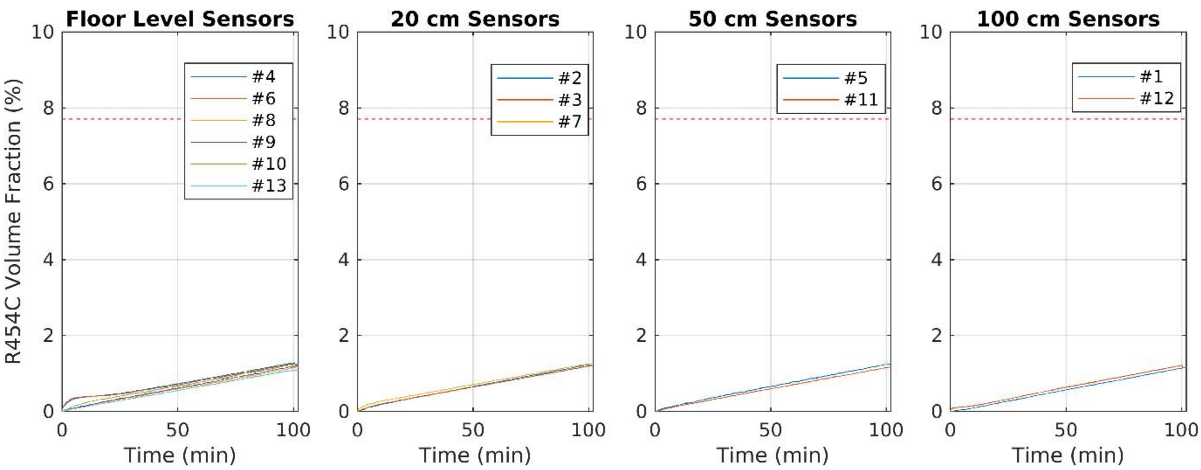


Figure A.8: Dispersion test #8 – top release, 20 g/min, condenser fan on, 2000 g charge.

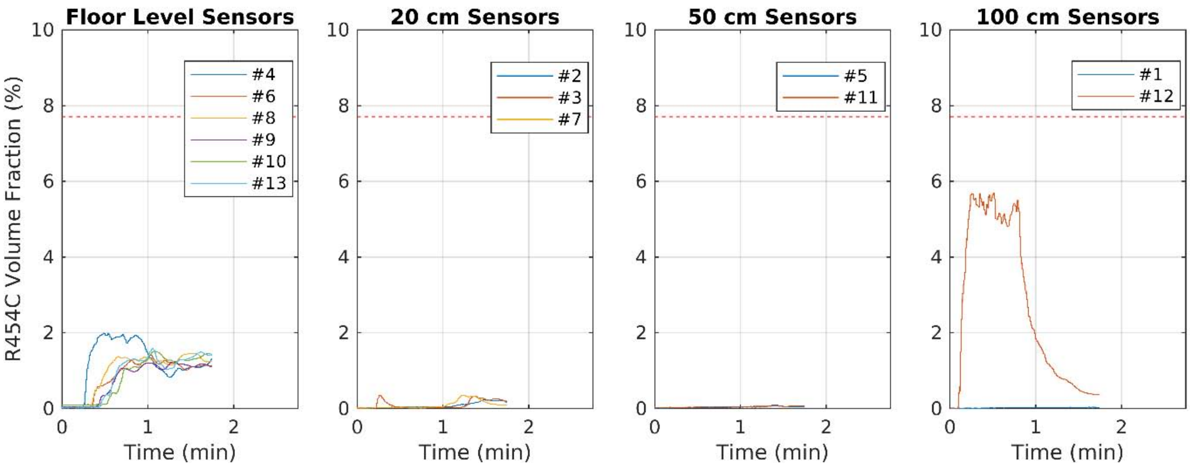


Figure A.9: Dispersion test #9 – top release, 200 g/min, condenser fan off, 150 g charge.

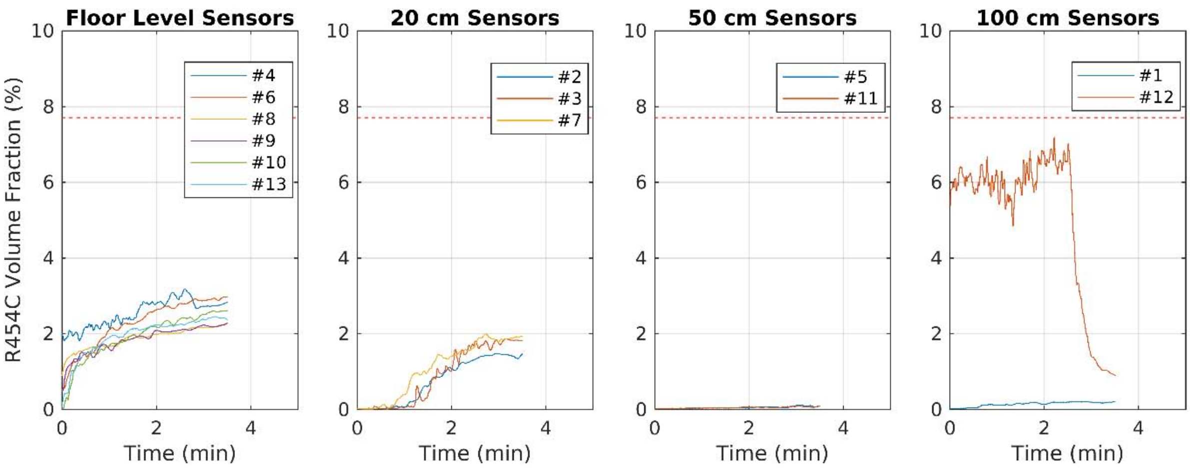


Figure A.10: Dispersion test #10 – top release, 200 g/min, condenser fan off, 600 g charge.

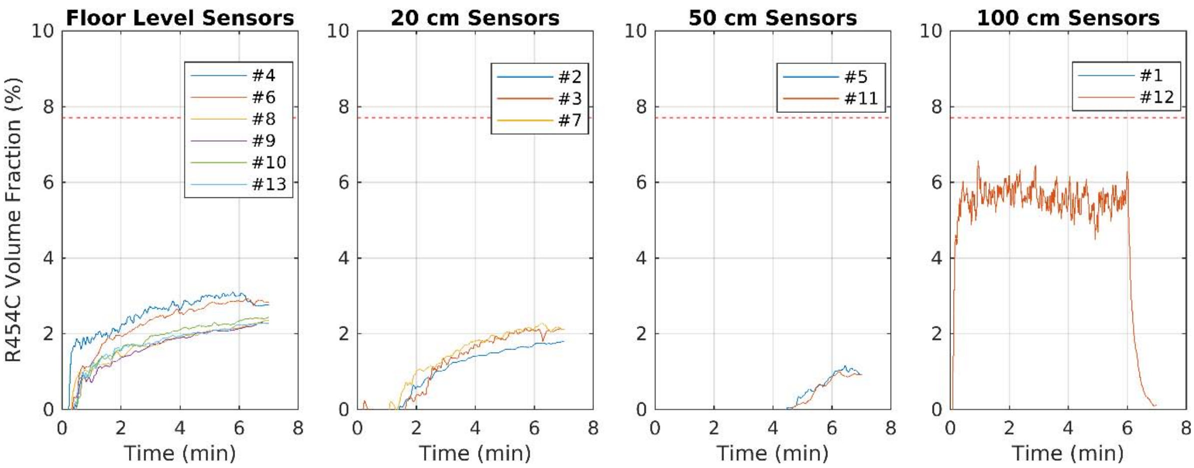


Figure A.11: Dispersion test #11 – top release, 200 g/min, condenser fan off, 1200 g charge.

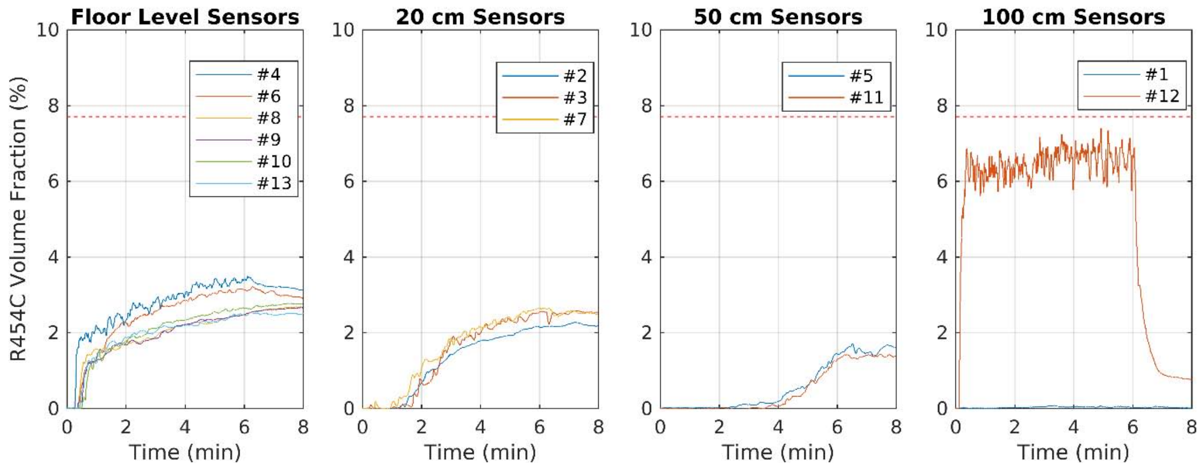


Figure A.12: Dispersion test #11 run 2 – top release, 200 g/min, condenser fan off, 1200 g charge.

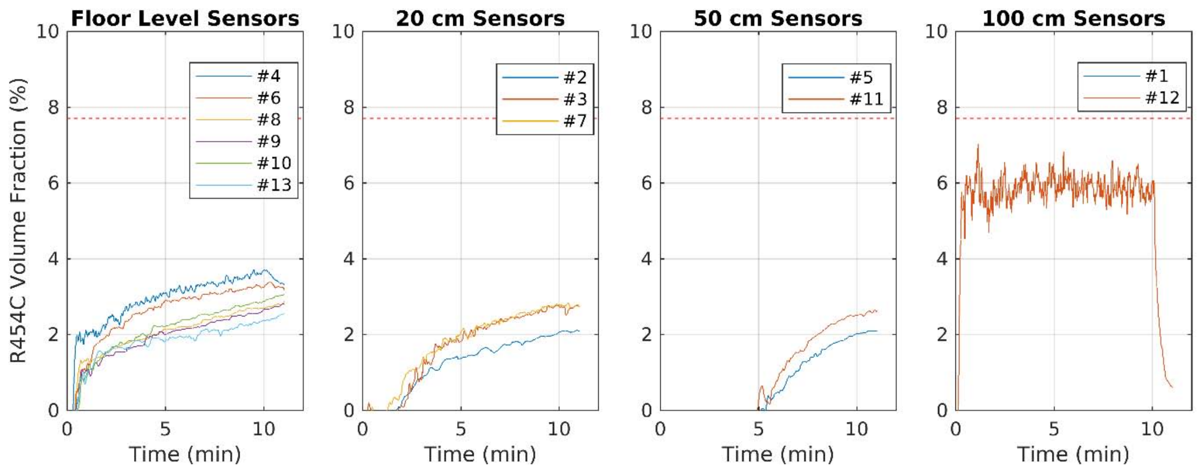


Figure A.13: Dispersion test #12 – top release, 200 g/min, condenser fan off, 2000 g charge.

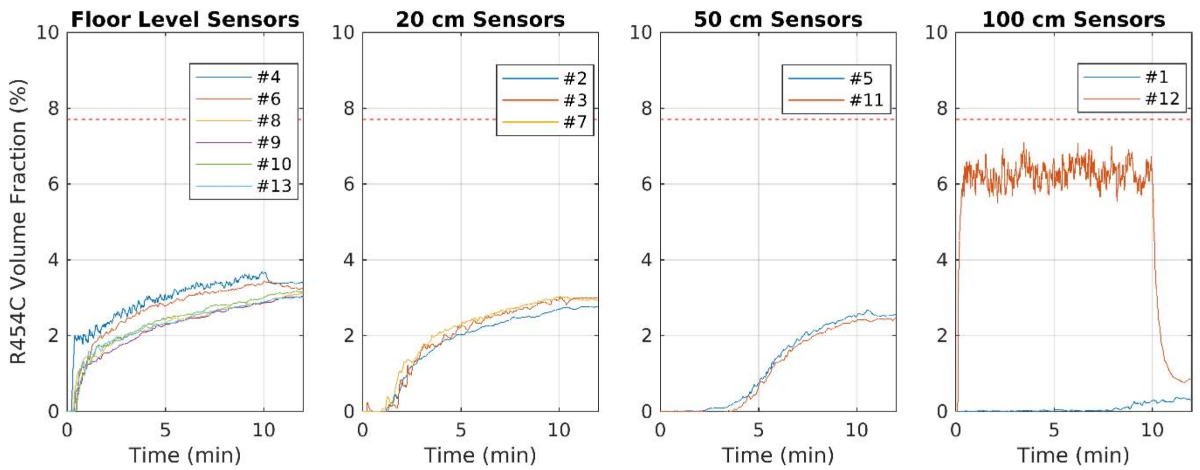


Figure A.14: Dispersion test #12 run 2 – top release, 200 g/min, condenser fan off, 2000 g charge.

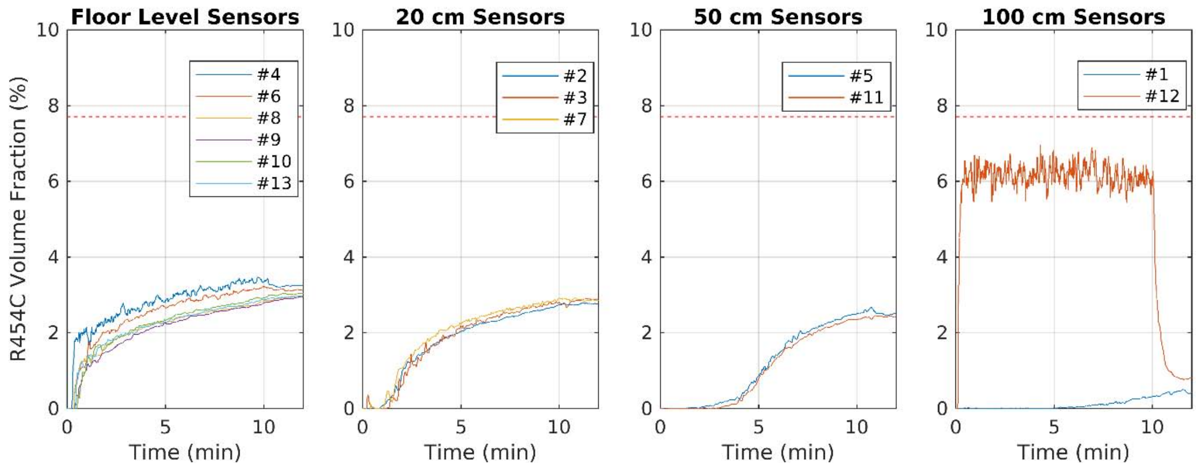


Figure A.15: Dispersion test #12 run 3 – top release, 200 g/min, condenser fan off, 2000 g charge.

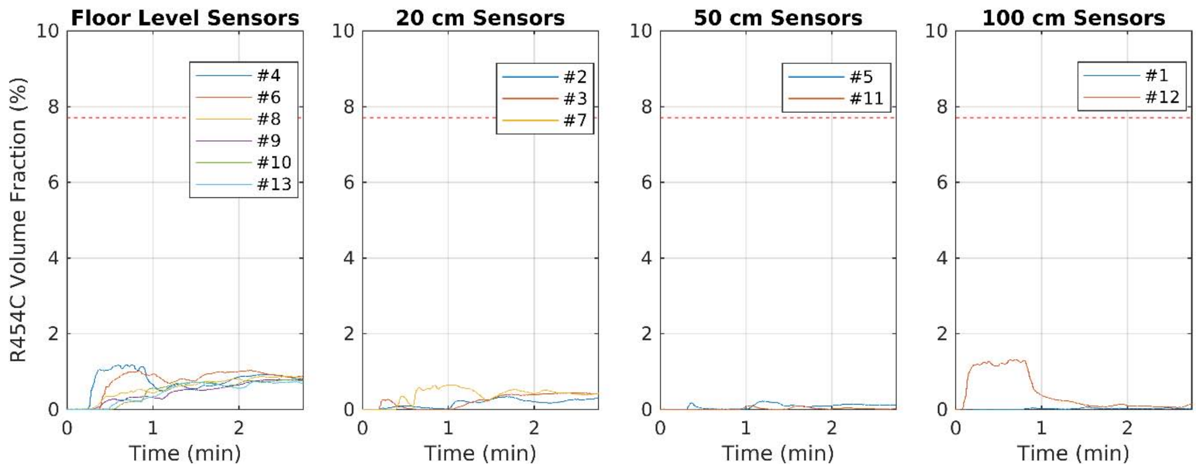


Figure A.16: Dispersion test #13 – top release, 200 g/min, condenser fan on, 150 g charge.

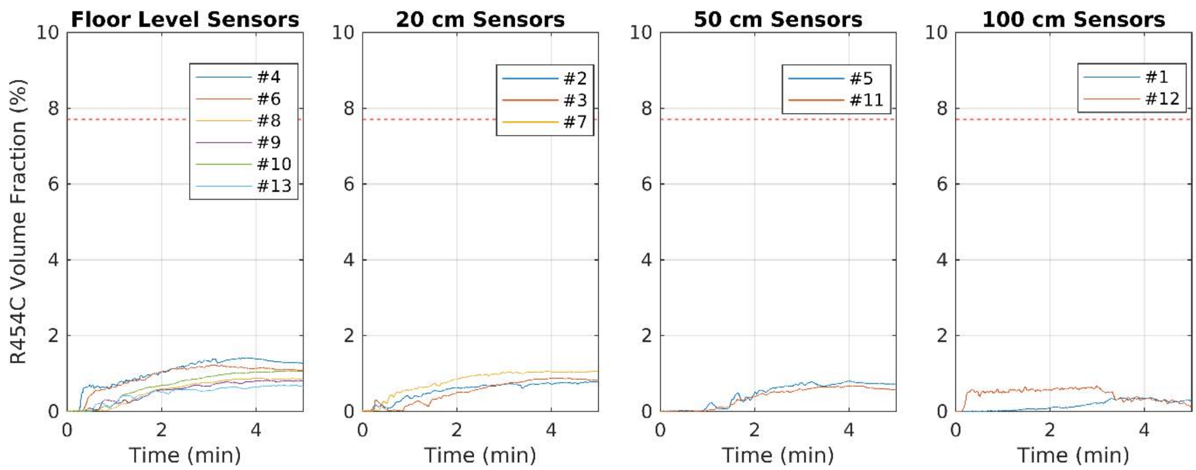


Figure A.17: Dispersion test #14 – top release, 200 g/min, condenser fan on, 600 g charge.

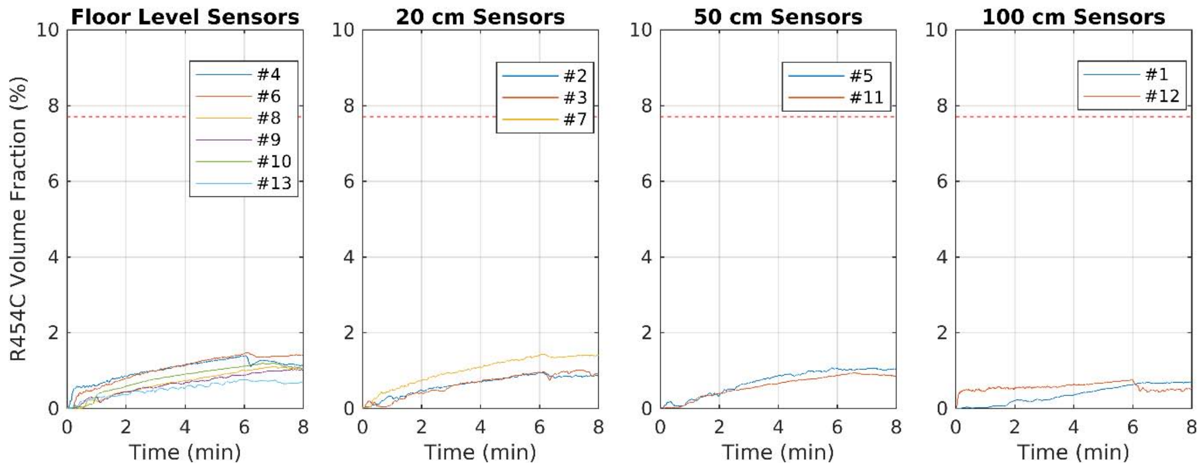


Figure A.18: Dispersion test #15 – top release, 200 g/min, condenser fan on, 1200 g charge.

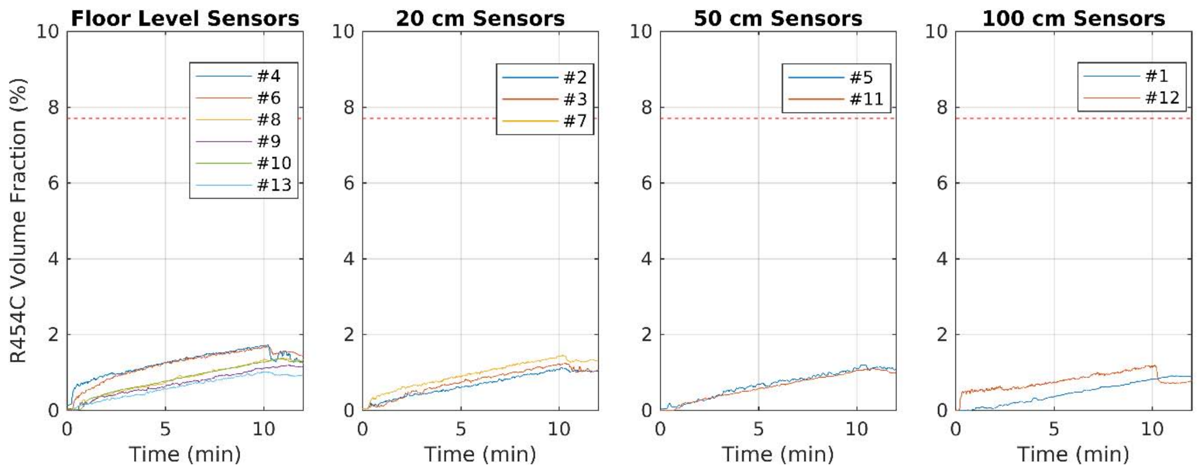


Figure A.19: Dispersion test #16 – top release, 200 g/min, condenser fan on, 2000 g charge.

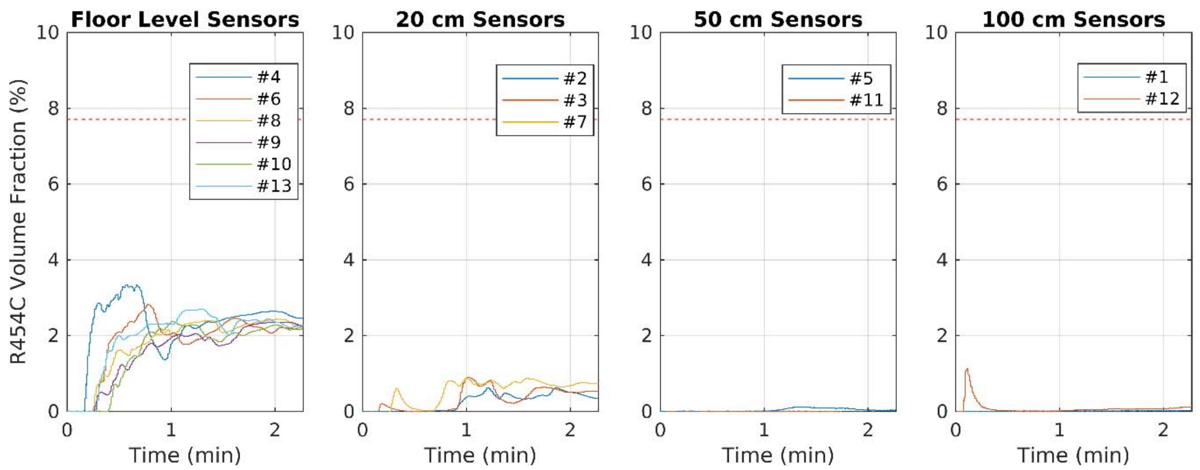


Figure A.20: Dispersion test #17 – top release, 550 g/min, condenser fan off, 150 g charge.

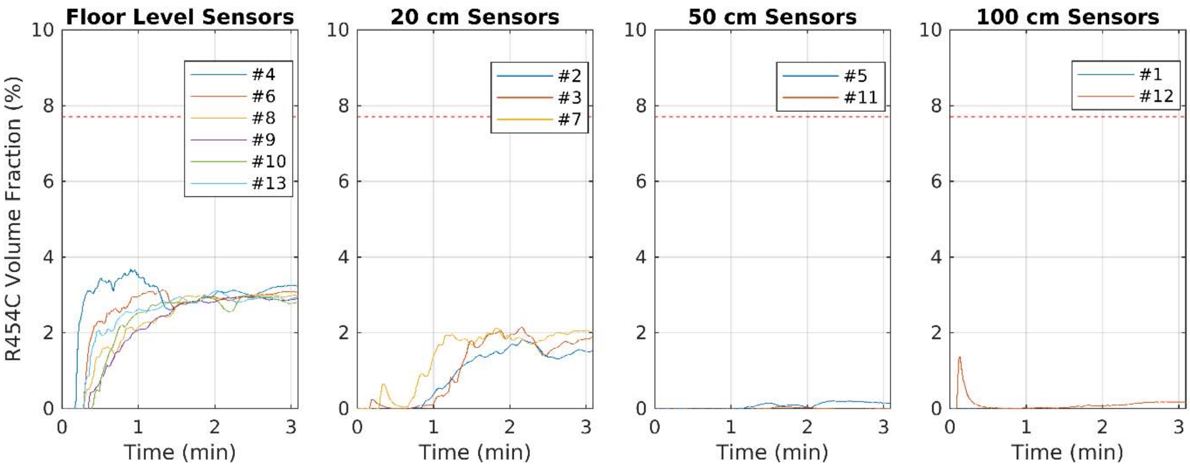


Figure A.21: Dispersion test #18 – top release, 550 g/min, condenser fan off, 600 g charge.

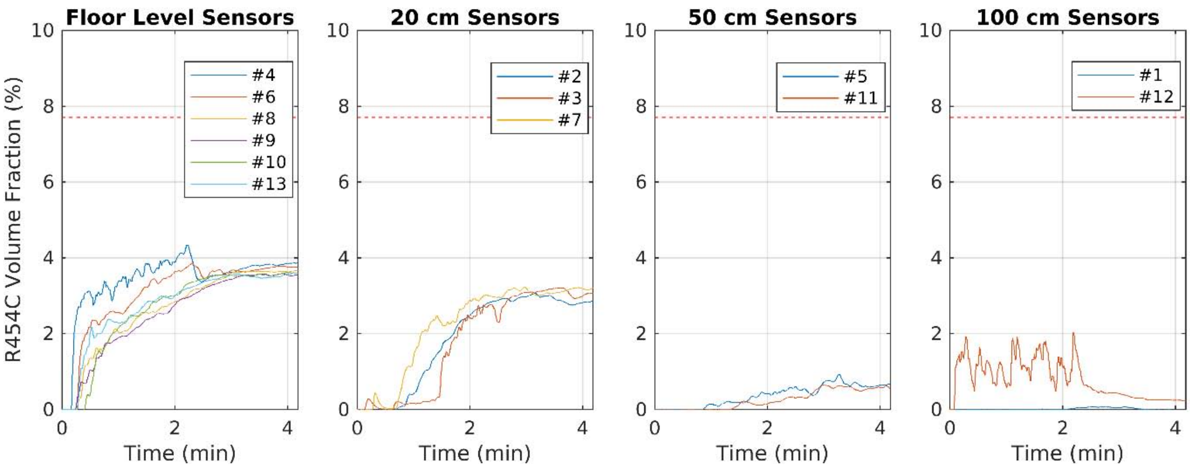


Figure A.22: Dispersion test #19 – top release, 550 g/min, condenser fan off, 1200 g charge.

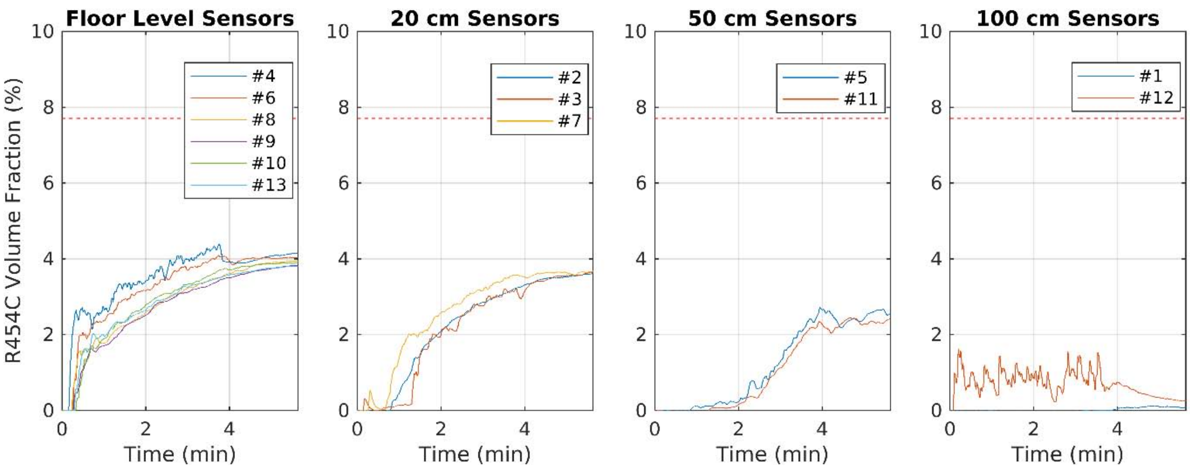


Figure A.23: Dispersion test #20 – top release, 550 g/min, condenser fan off, 2000 g charge.

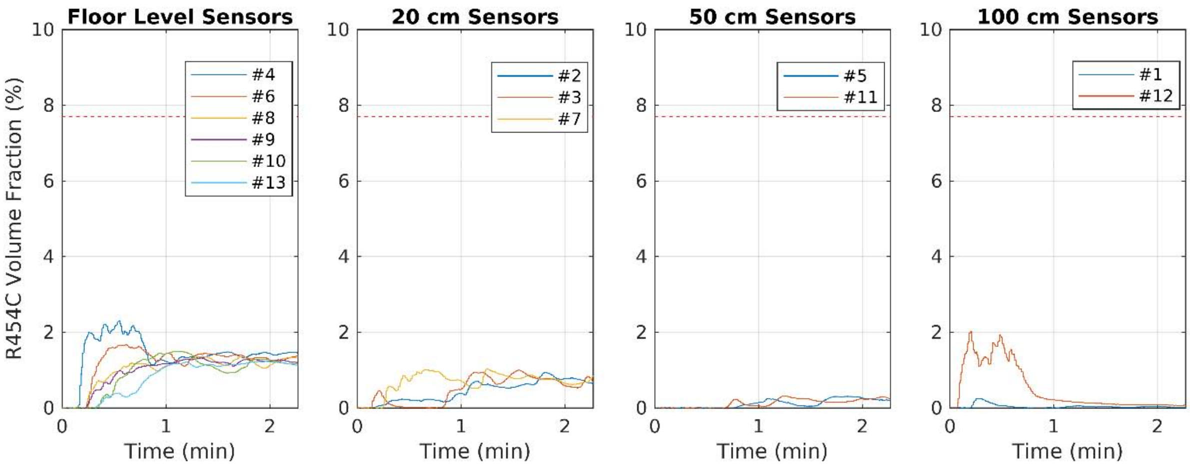


Figure A.24: Dispersion test #21 – top release, 550 g/min, condenser fan on, 150 g charge.

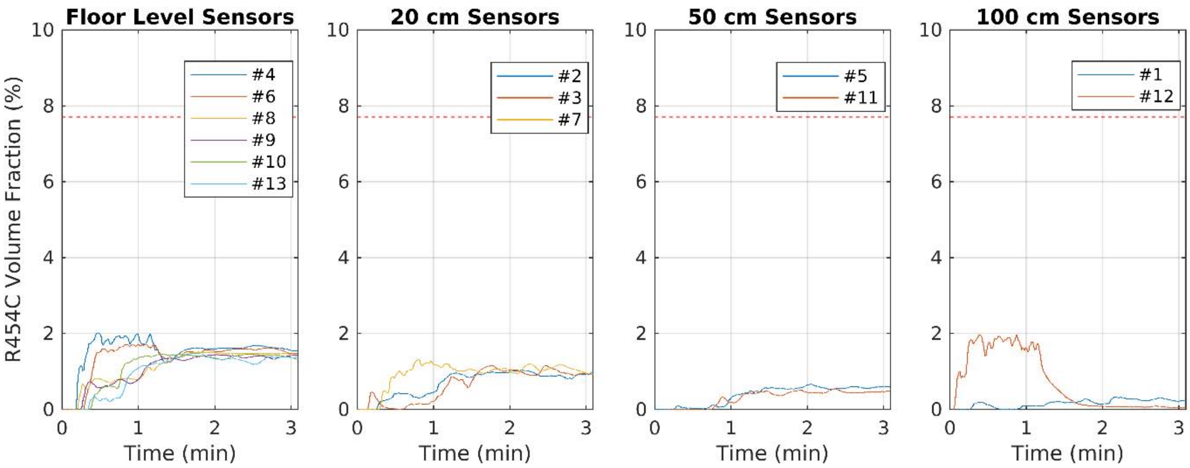


Figure A.25: Dispersion test #22 – top release, 550 g/min, condenser fan on, 600 g charge.

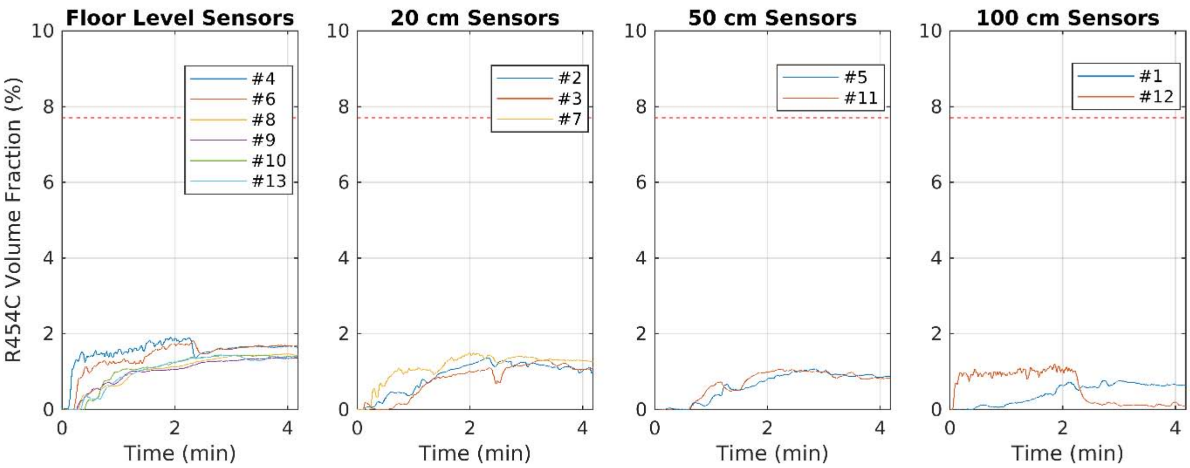


Figure A.26: Dispersion test #23 – top release, 550 g/min, condenser fan on, 1200 g charge.

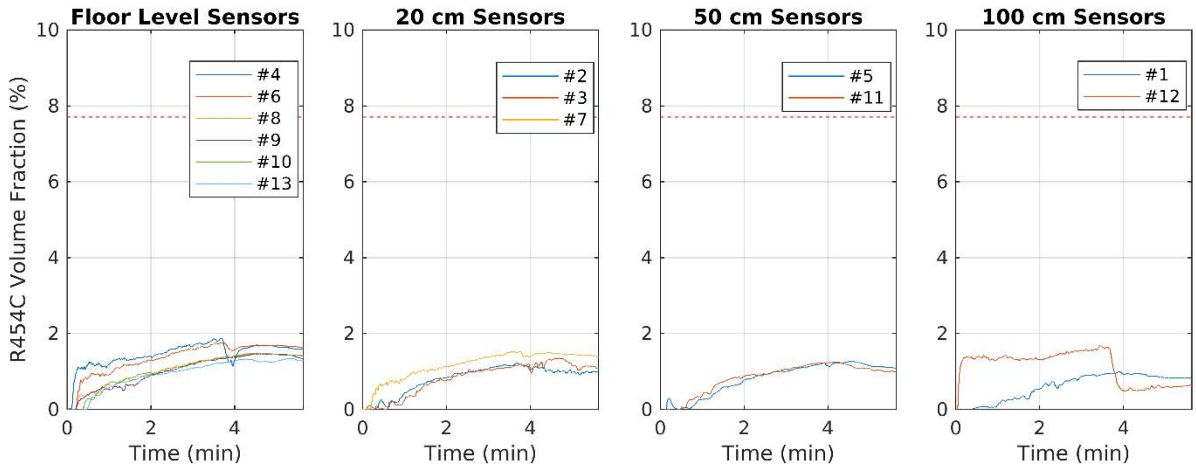


Figure A.27: Dispersion test #24 – top release, 550 g/min, condenser fan on, 2000 g charge.

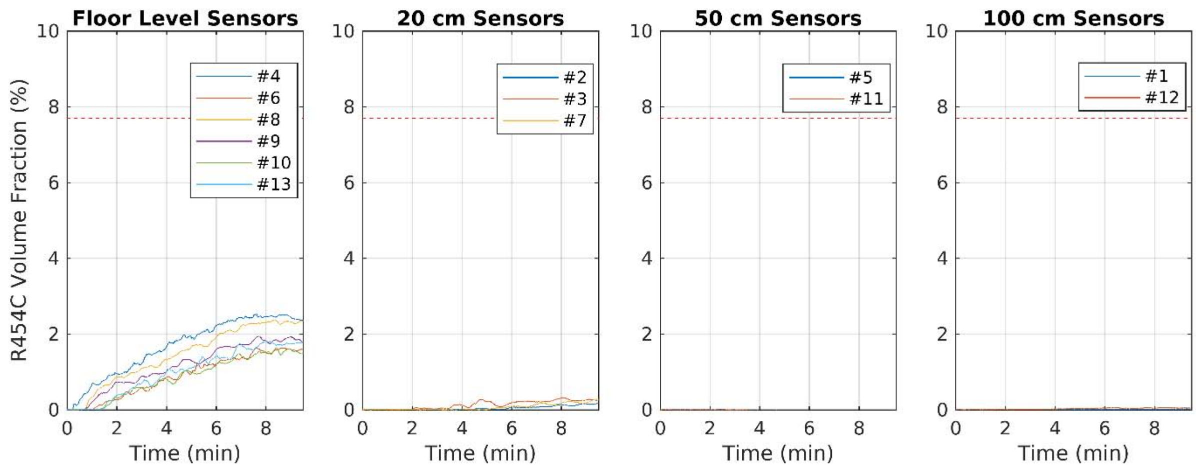


Figure A.28: Dispersion test #25 – bottom release, 20 g/min, condenser fan off, 150 g charge.

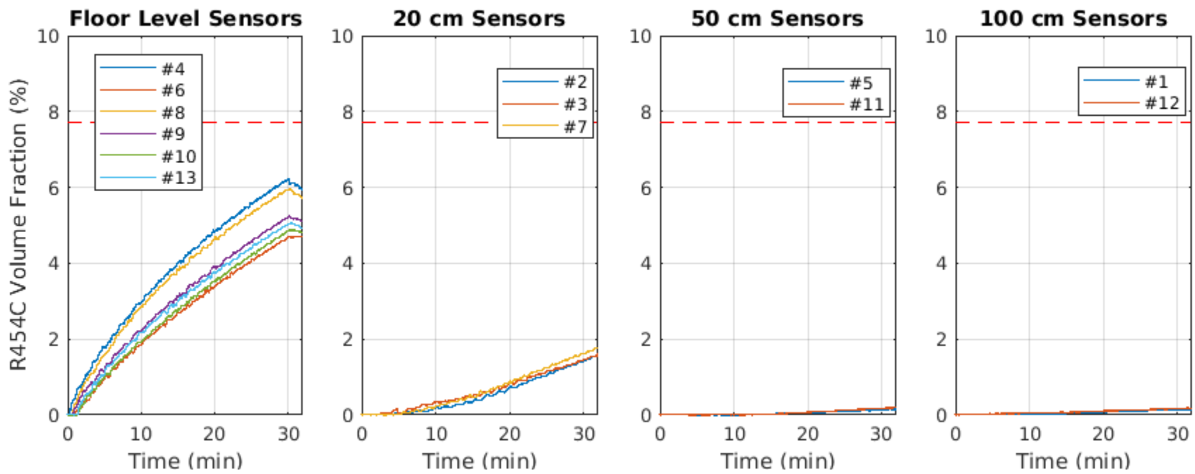


Figure A.29: Dispersion test #26 – bottom release, 20 g/min, condenser fan off, 600 g charge.

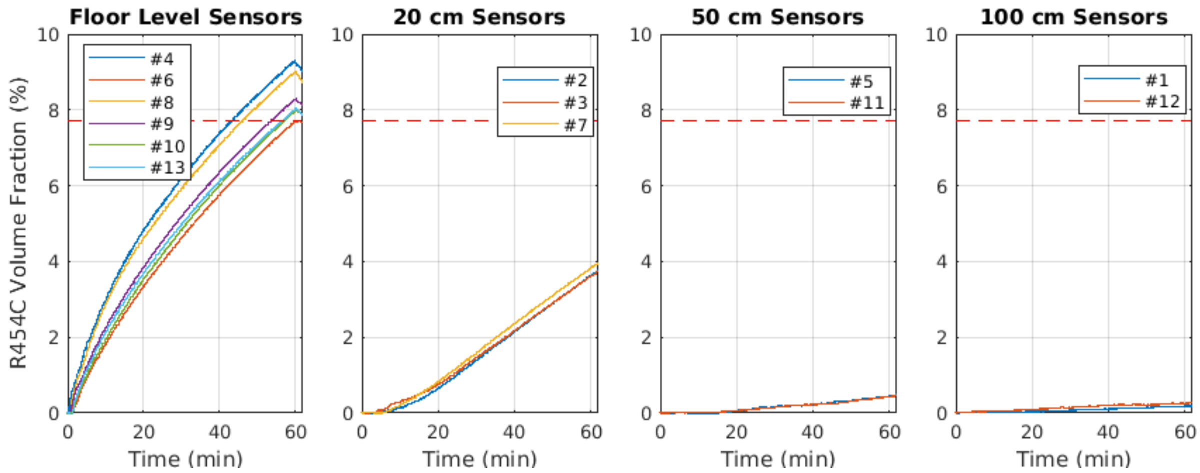


Figure A.30: Dispersion test #27 – bottom release, 20 g/min, condenser fan off, 1200 g charge.

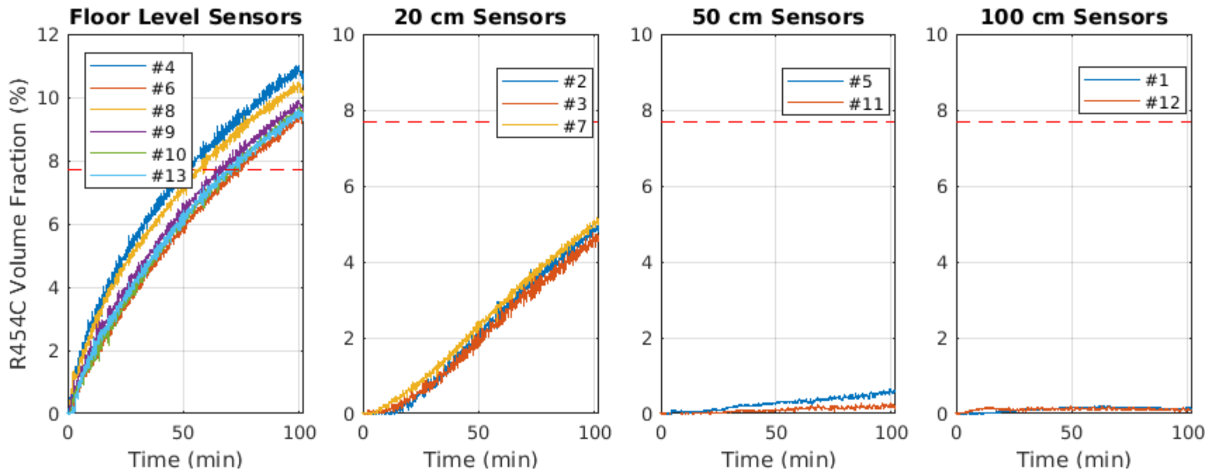


Figure A.31: Dispersion test #28 – bottom release, 20 g/min, condenser fan off, 2000 g charge.

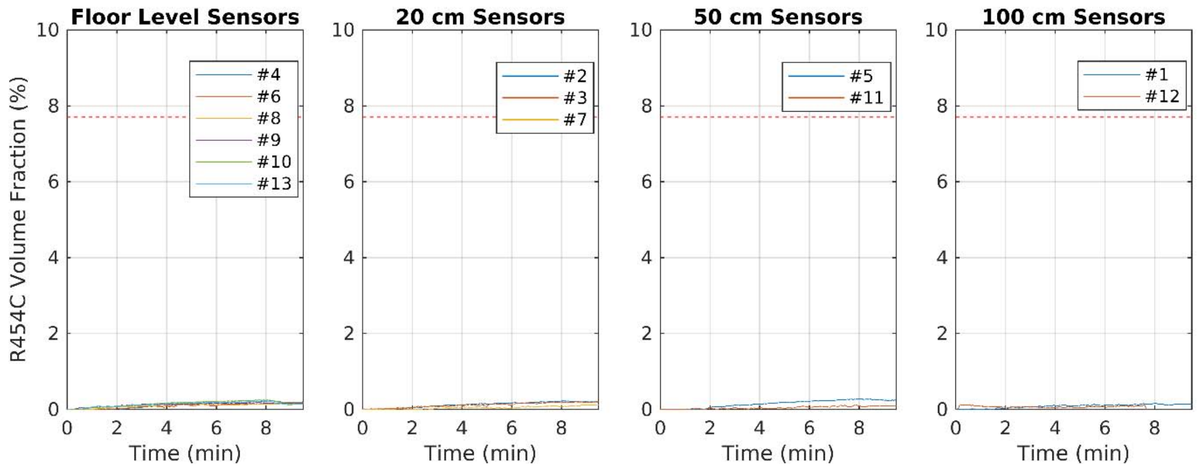


Figure A.32: Dispersion test #29 – bottom release, 20 g/min, condenser fan on, 150 g charge.

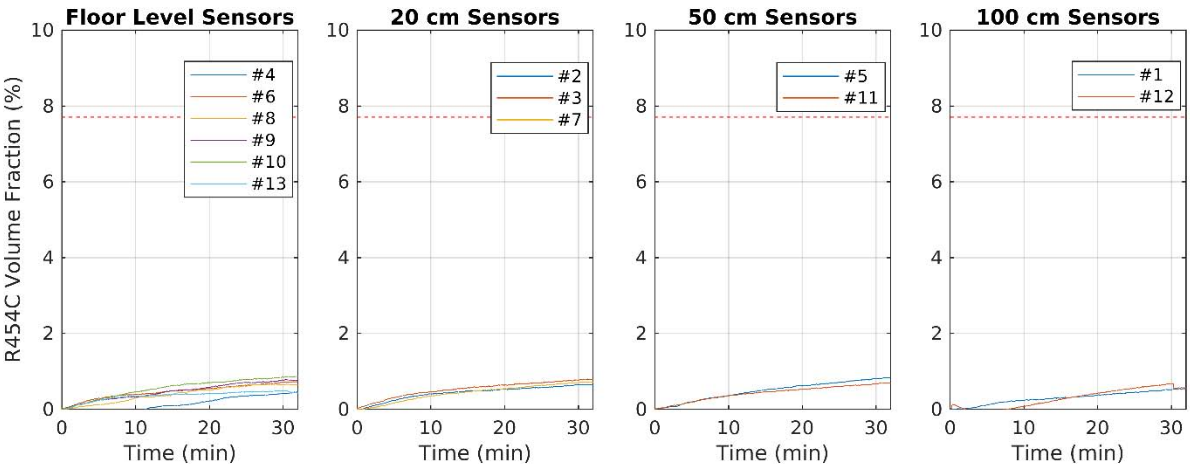


Figure A.33: Dispersion test #30 – bottom release, 20 g/min, condenser fan on, 600 g charge.

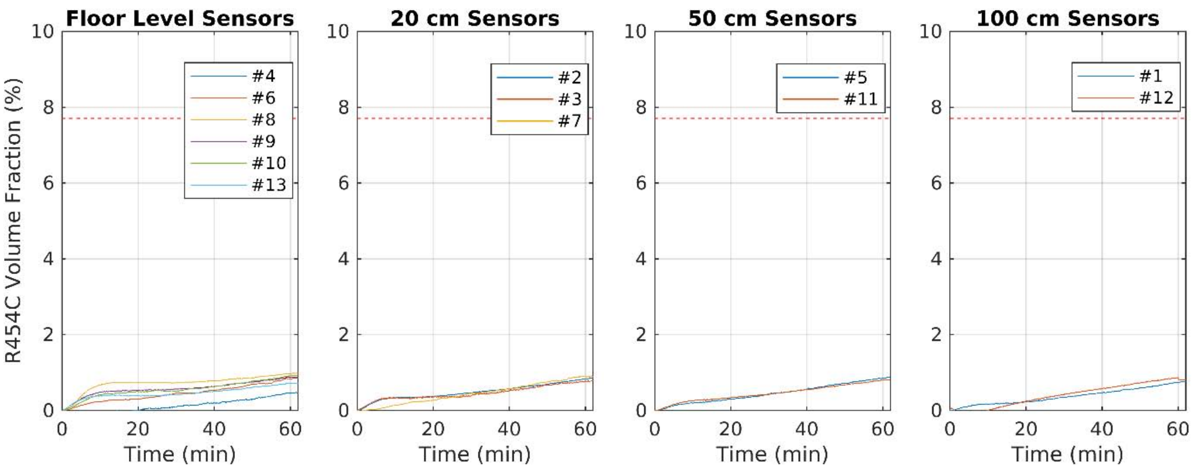


Figure A.34: Dispersion test #31 – bottom release, 20 g/min, condenser fan on, 1200 g charge.

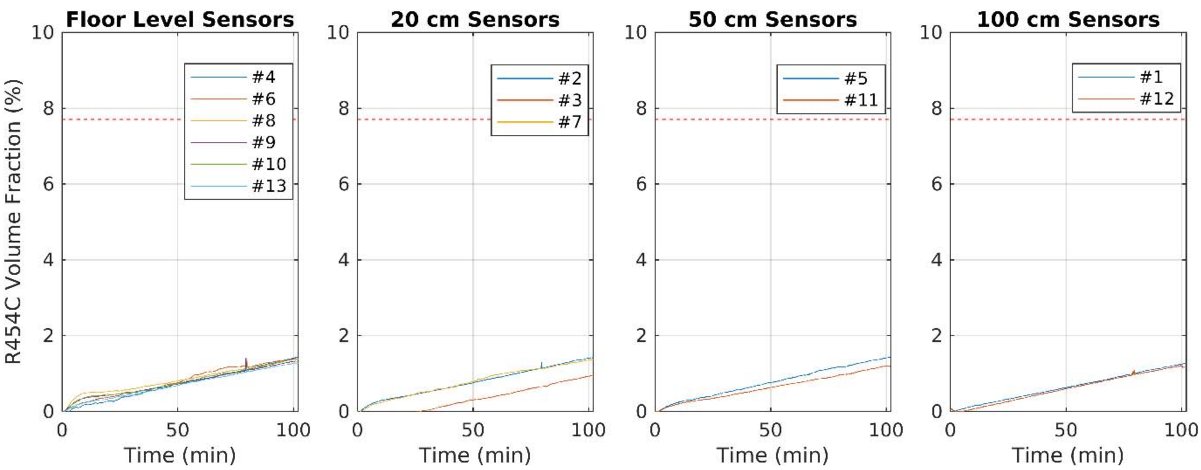


Figure A.35: Dispersion test #32 – bottom release, 20 g/min, condenser fan on, 2000 g charge.

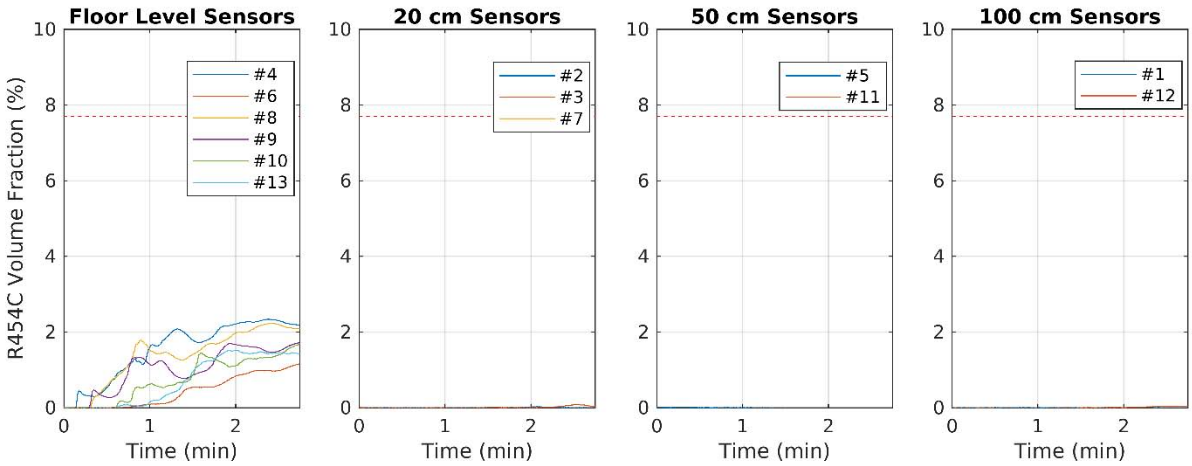


Figure A.36: Dispersion test #33 – bottom release, 200 g/min, condenser fan off, 150 g charge.

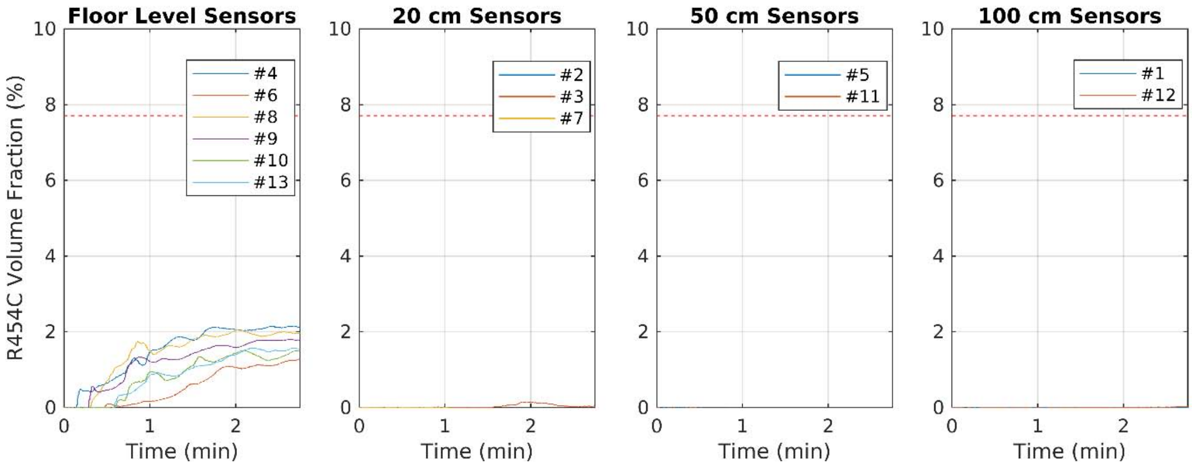


Figure A.37: Dispersion test #33 run 2 – bottom release, 200 g/min, condenser fan off, 150 g charge.

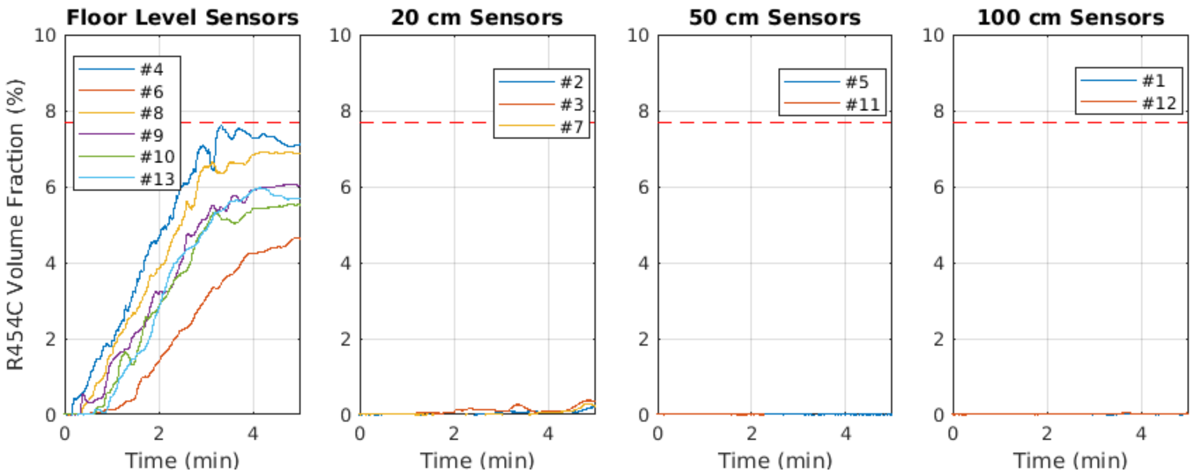


Figure A.38: Dispersion test #34 – bottom release, 200 g/min, condenser fan off, 600 g charge.

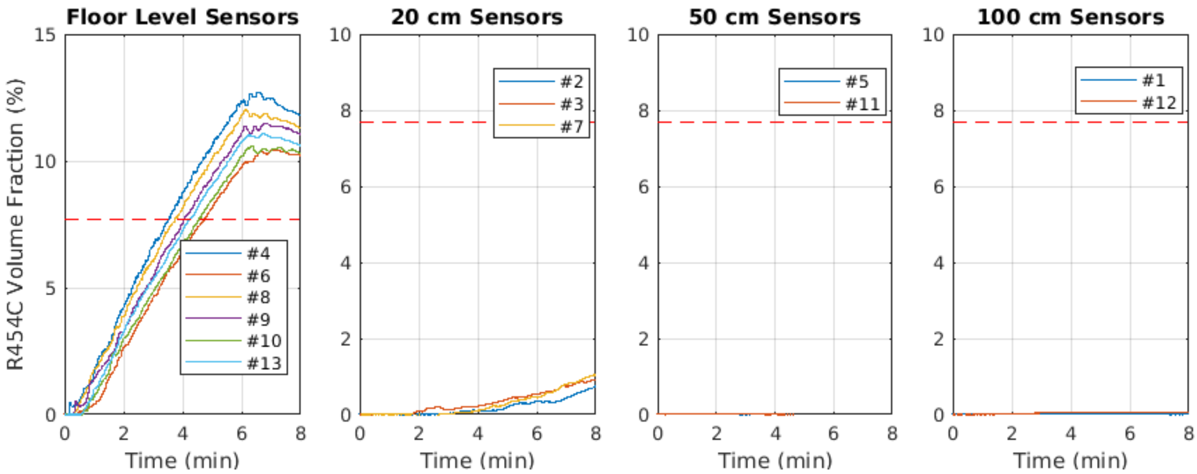


Figure A.39: Dispersion test #35 – bottom release, 200 g/min, condenser fan off, 1200 g charge.

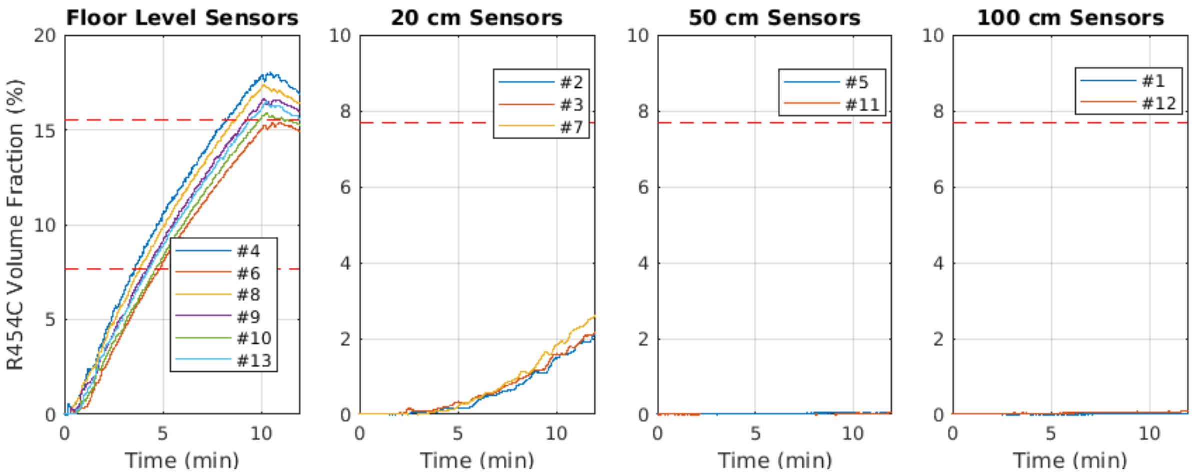


Figure A.40: Dispersion test #36 – bottom release, 200 g/min, condenser fan off, 2000 g charge.

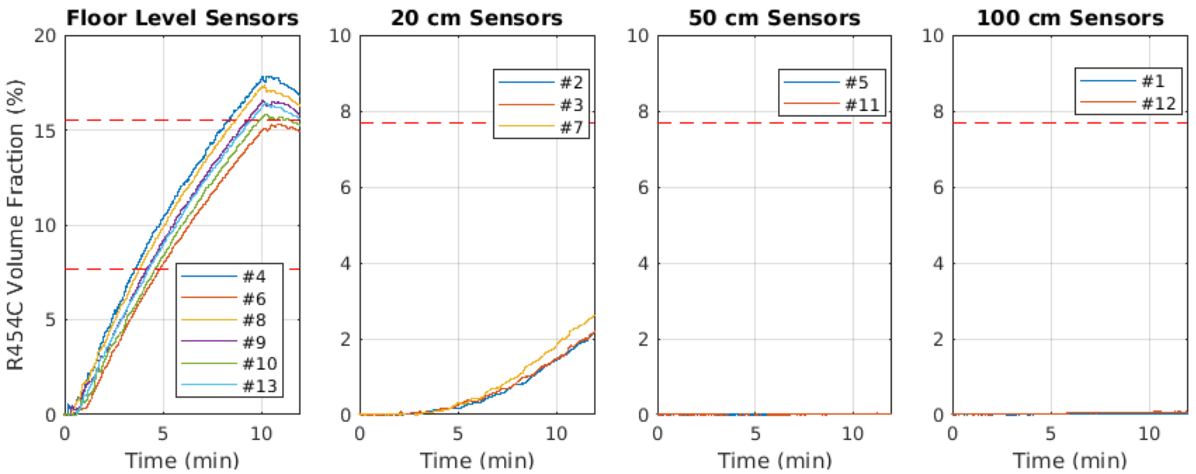


Figure A.41: Dispersion test #36 run 2 – bottom release, 200 g/min, condenser fan off, 2000 g charge.

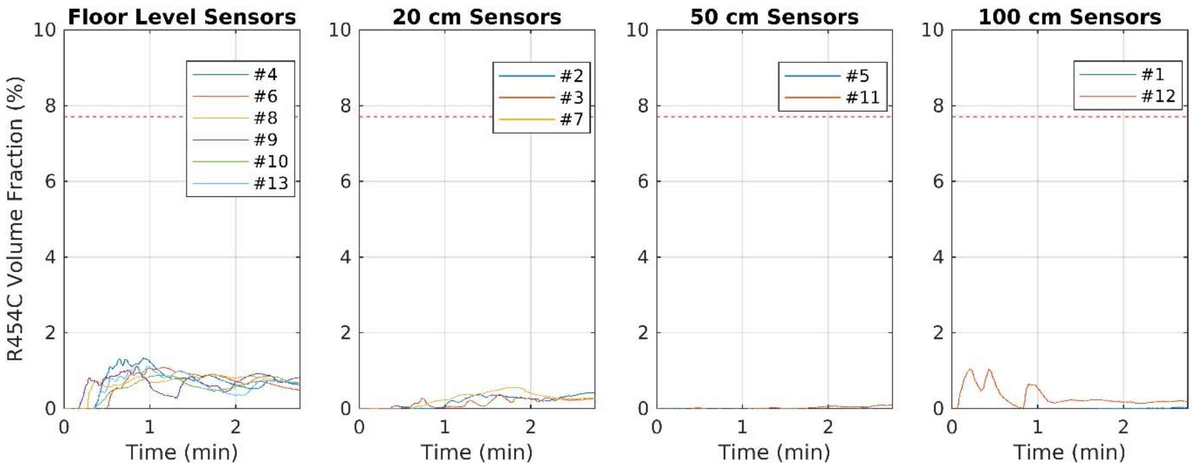


Figure A.42: Dispersion test #37 – bottom release, 200 g/min, condenser fan on, 150 g charge.

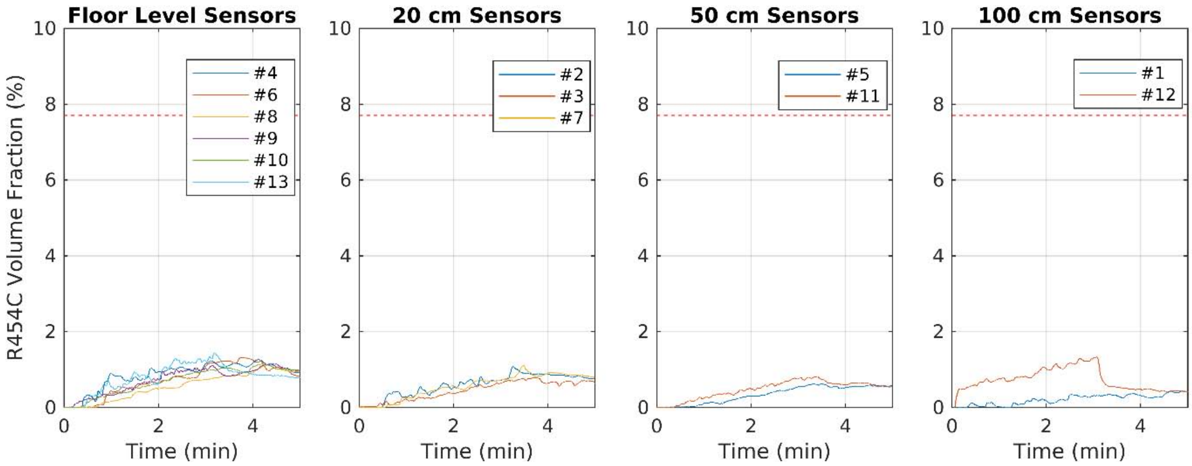


Figure A.43: Dispersion test #38 – bottom release, 200 g/min, condenser fan on, 600 g charge.

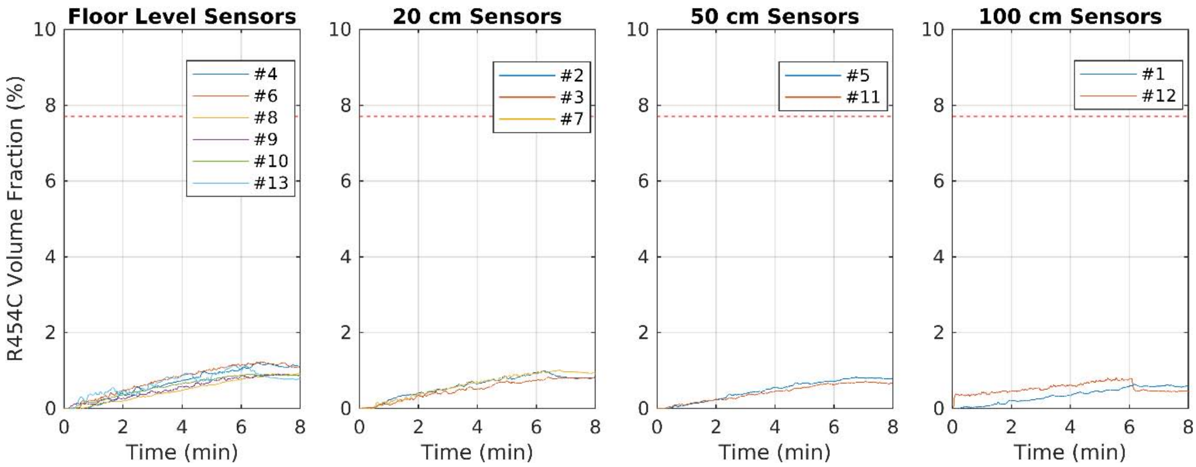


Figure A.44: Dispersion test #39 – bottom release, 200 g/min, condenser fan on, 1200 g charge.

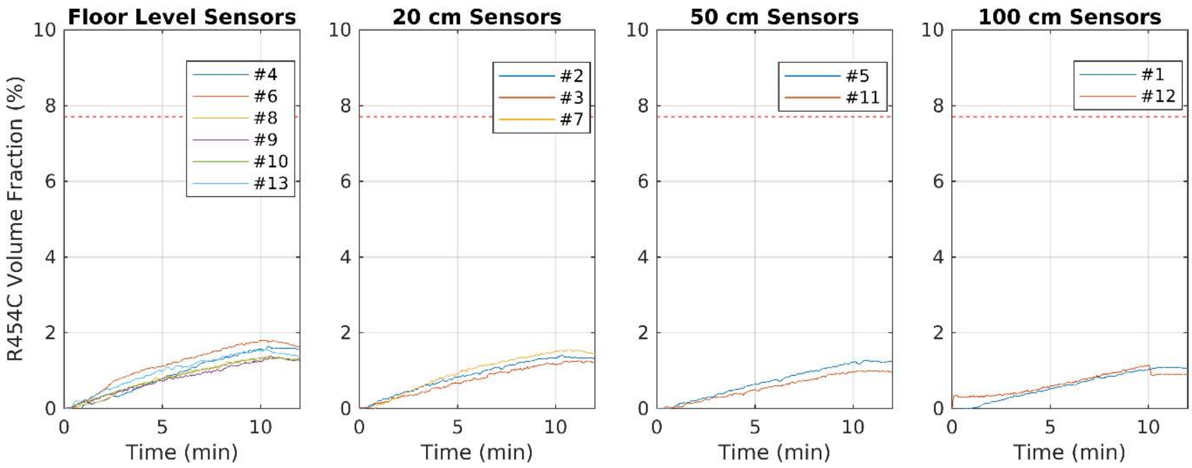


Figure A.45: Dispersion test #40 – bottom release, 200 g/min, condenser fan on, 2000 g charge.

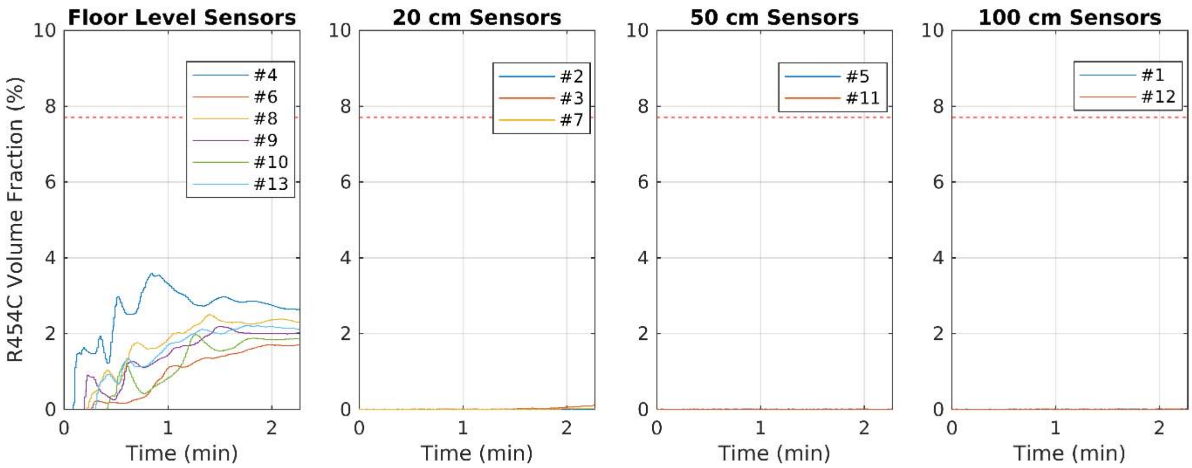


Figure A.46: Dispersion test #41 – bottom release, 550 g/min, condenser fan off, 150 g charge.

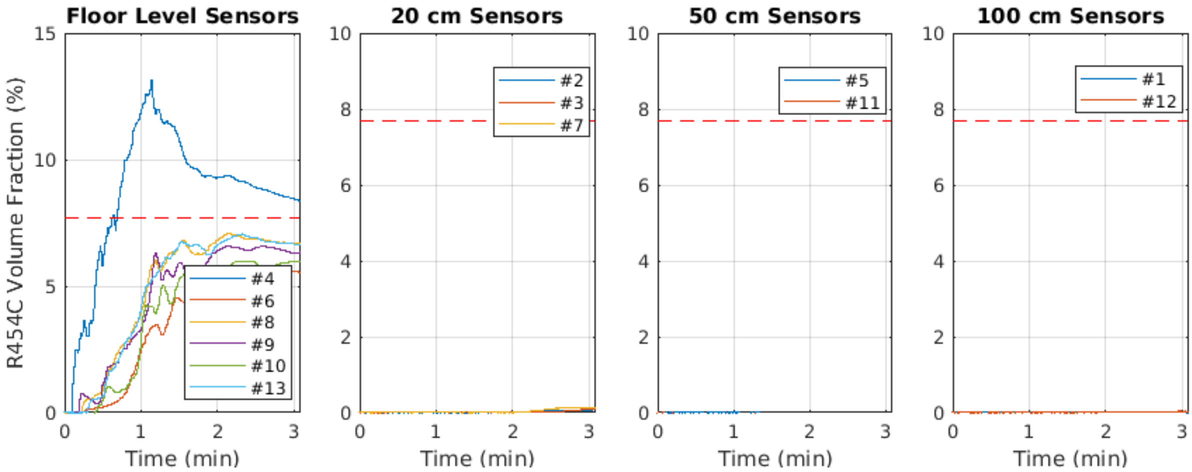


Figure A.47: Dispersion test #42 – bottom release, 550 g/min, condenser fan off, 600 g charge.

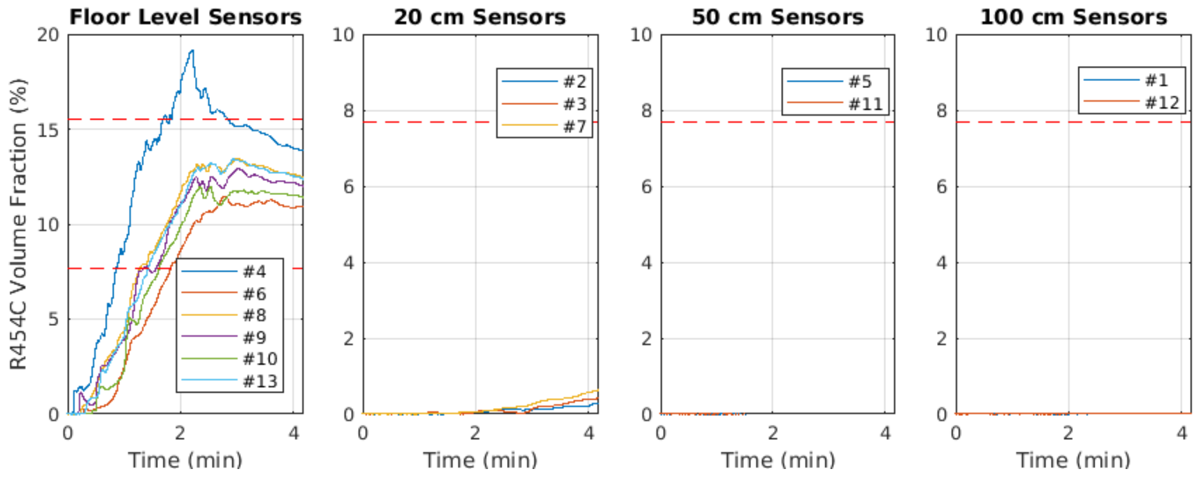


Figure A.489: Dispersion test #43 – bottom release, 550 g/min, condenser fan off, 1200 g charge.

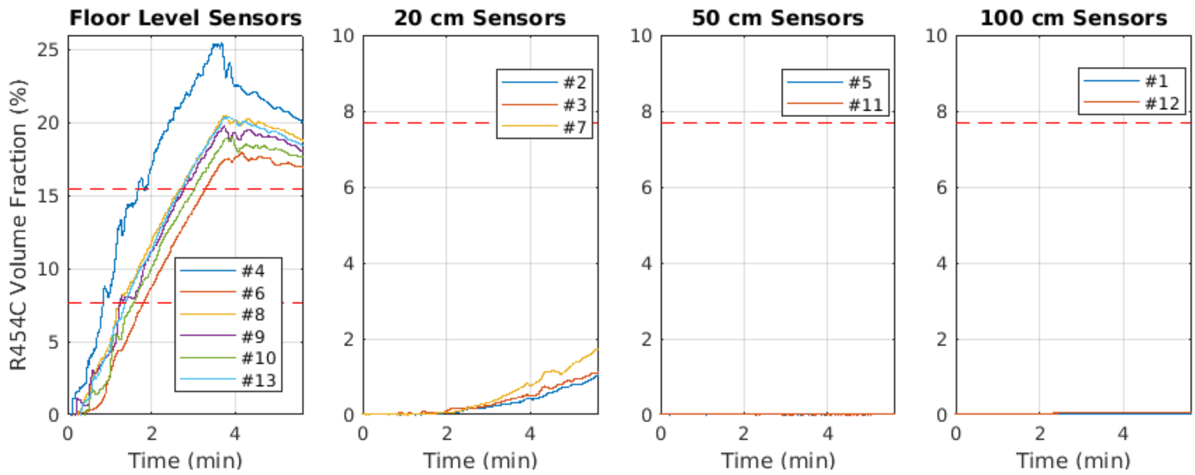


Figure A.49: Dispersion test #44 – bottom release, 550 g/min, condenser fan off, 2000 g charge.

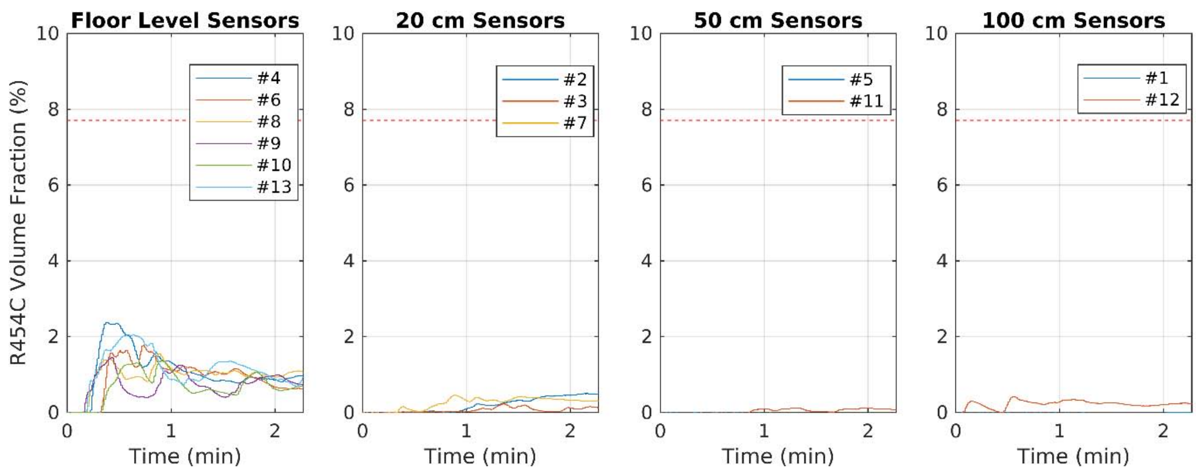


Figure A.50: Dispersion test #45 – bottom release, 550 g/min, condenser fan on, 150 g charge.

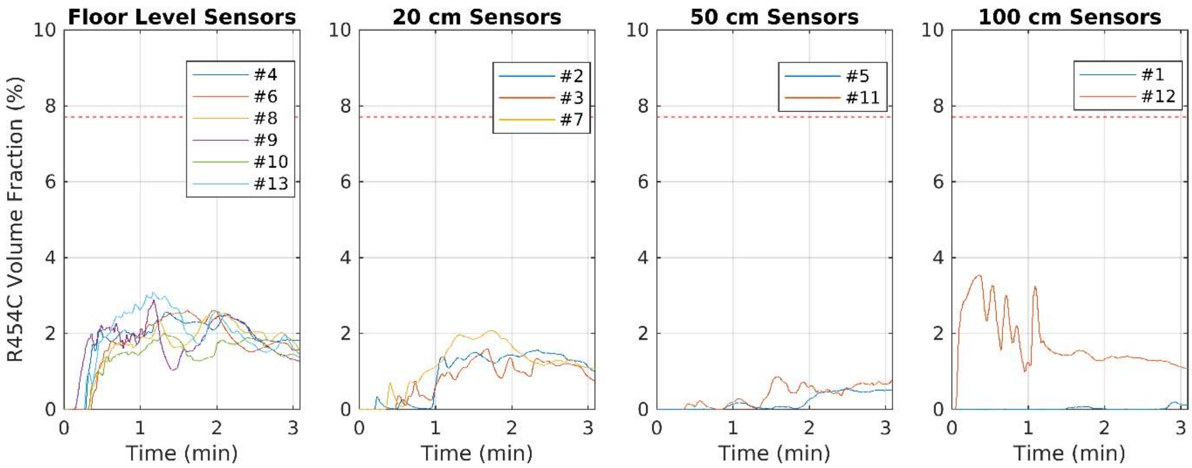


Figure A.51: Dispersion test #46 – bottom release, 550 g/min, condenser fan on, 600 g charge.

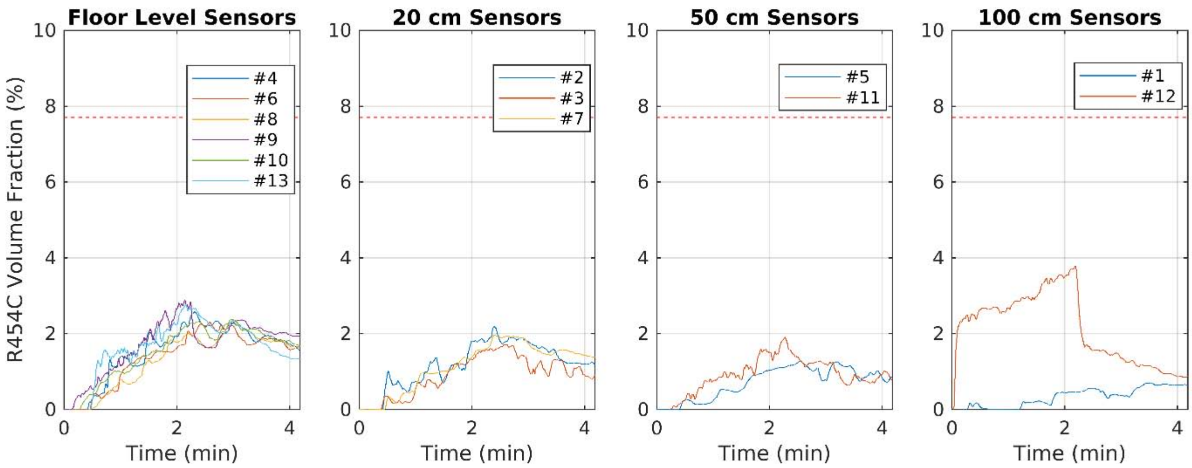


Figure A.52: Dispersion test #47 – bottom release, 550 g/min, condenser fan on, 1200 g charge.

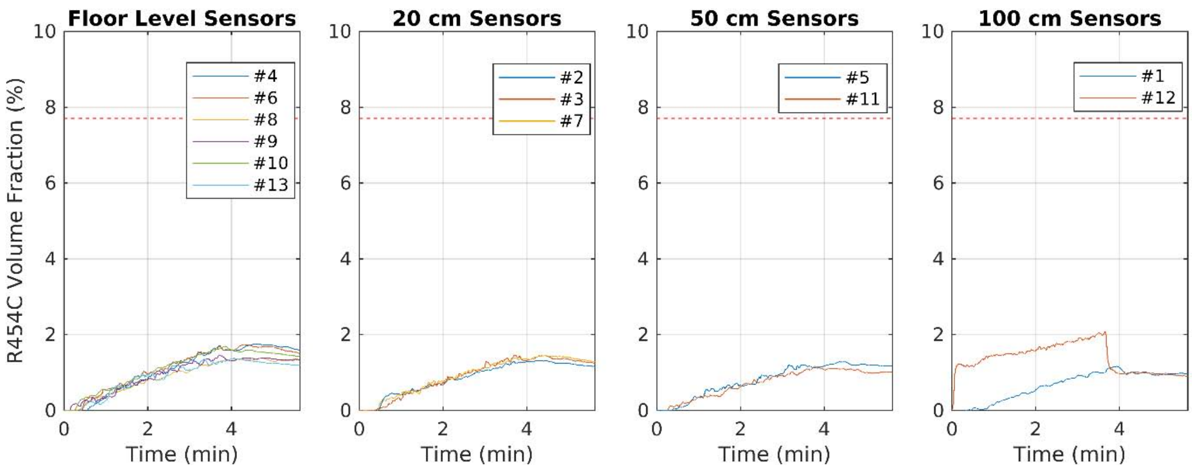


Figure A.53: Dispersion test #48 – bottom release, 550 g/min, condenser fan on, 2000 g charge.