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A2L Refrigerants Leaks and Ignitions Testing under Whole Room Scale

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ABSTRACT

Environmental concerns raised by high global warming potential (GWP) refrigerants have triggered a series of activities around the world to curtail the use of hydrofluorocarbons (HFCs). Many of the promising alternative refrigerants being investigated are mildly flammable and fall under the A2L safety classification of ASHRAE 34. In an effort to properly address A2L refrigerants in safety standards, the Air-Conditioning, Heating, and Refrigeration Technology Institute (AHRTI) undertook a research project to investigate refrigerant leaks and ignition testing under whole scale room conditions.

This paper summarizes refrigerant leak and ignition tests for A2L refrigerants R-32, R-452B, R-455A and R-457A. The work included two main tasks. The first involved testing R32 and R452B under a controlled environment to explore factors affecting the refrigerants' ignition. These factors include refrigerant leak rates, leak locations, leak opening size and oil effect. In the second task, tests were conducted under whole room scale for typical air-conditioning and refrigeration configurations. The whole room testing simulated large refrigerant leaks with ignition sources present from a packaged terminal unit, a residential split AC, a rooftop unit, a reach-in cooler and a walk-in cooler under various scenarios. Key observations will be summarized and future research work will be discussed.

1. INTRODUCTION

Regulatory efforts to reduce global warming requires that the air conditioning and refrigeration industry evaluates lower-GWP refrigerants as alternatives to the high GWP refrigerants used today in the majority of HVACR applications. The AHRI Low-GWP Alternative Refrigerants Evaluation Program (Wang et al, 2014 and 2016) has shown that many promising alternatives are classified as A2L (mildly flammable, such as HFOs) or A3 (flammable, such as hydrocarbons) according to ASHRAE Standard 34 (ASHRAE, 2016).

In order to support code and standard activities related to the use of flammable refrigerants, AHRI conducted a survey to committees and working groups working on flammable refrigerants related standards. The survey was focused on identifying existing knowledge gaps of using flammable refrigerants. Among the survey responses, the top priority research needs were identified below:

- Whole room or real life leaks, with ignition sources present, are needed to validate or recalibrate current AHRI and OEM risk assessments.
- The HVAC industry needs to understand the risk/consequence after refrigerant ignition, in order to establish quantified risk tolerance limits for severity of event rather than just probability of ignition.
- The HVAC industry needs to assess the ability of 2L refrigerants to sustain an ignition (with % oil included), and possibly cause a secondary combustion event compared to current refrigerant/lubricant systems which are proven in use.

To address these identified needs, AHRTI launched a research project to conduct whole room scale testing. The testing was conducted by UL at its test facility in Northbrook, IL. The objective of the project was to conduct refrigerant leak and ignition testing under real life conditions to understand the risk associated with the use of A2L refrigerants as opposed to the A1 refrigerants currently in use while considering ambient conditions (temperature and humidity) and refrigerant lubricants (Gandhi et al, 2017).

2. TEST SETUP AND PROCEDURES

The project consisted of parametric testing in ISO room and scenario testing in whole room scale. Both involved releasing liquid A2L refrigerants into spaces with variety of viable ignition sources present. The refrigerant release system is illustrated in Figure 1. Its two main components are a pressurizer tank and a release tank that are equipped with accessories such as control valves and temperature and pressure measurement. Both tanks contained the same refrigerant and were submerged in heated water tanks to achieve desired pressure and temperature conditions. The pressurizer tank ensures the release tank to release liquid refrigerant to the test room at a constant rate. The refrigerant release rate was controlled by a control valve that continuously adjusts its opening according to the feedback from the mass flow meter. For tests including lubricating oil, the oil was mixed with the refrigerant between the mass flow meter and the control valve using a gear pump.

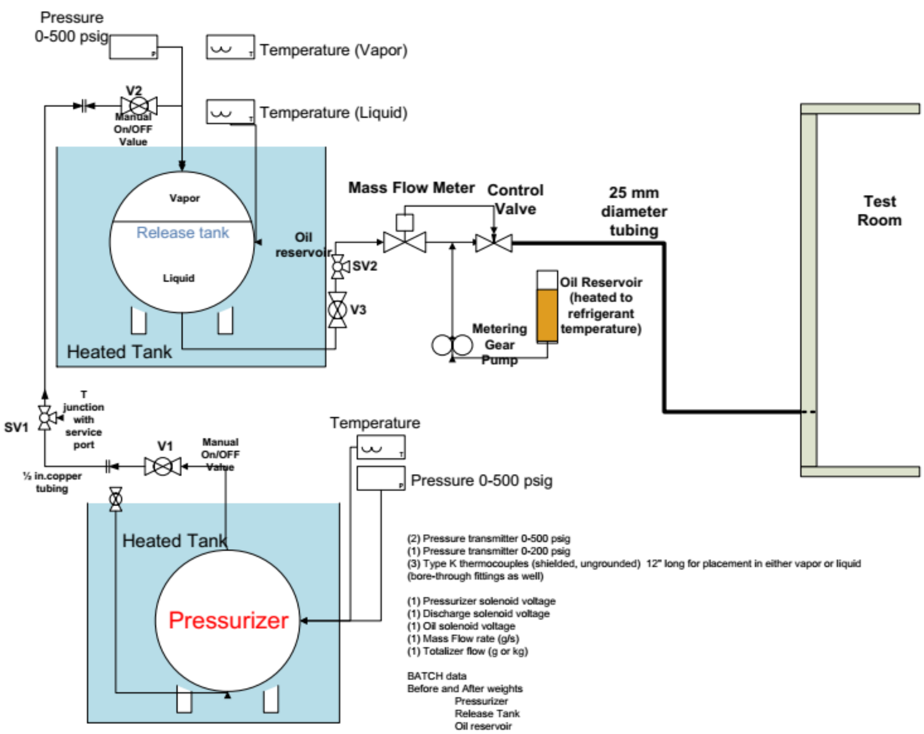

Figure 1: Schematic of the refrigerant release mechanism setup (Gandhi et al, 2017)

2.1 Task 1: Parametric Testing in ISO Room

The purpose of this testing is to investigate how variables (ambient, refrigerant amount etc.) influence the results in this standardized testing rig. An ISO 9705 test room was constructed within the test facility (ISO, 2016). The dimensions of the room are 12 x 8 x 8 ft (3.7 x 2.4 x 2.4 m). A 6 x 3 x 3 ft (1.83 x 0.91 x 0.91 m) box was built in the middle of the room to serve as an obstruction (e.g., furniture). The room layout, key instrumentation and ignition sources locations are shown in Figure 2.

The test room initially had a deflagration vent opening that was 2 ft.-8 in. by 2 ft (0.8 m x 0.6 m) in size and closed with a thin plastic sheet. The plastic sheet was supposed to be perforated due to the pressure rise and avoid the overpressure if an ignition occurs. However, the sheet did not open soon enough to prevent the overpressure for the first series of tests. The vent opening was enlarged for all later tests to 2 ft-8 inches wide and 3 ft. tall (0.8 m x 0.9

m), and located at 5 ft. (1.5 m) above the floor. Instead of a thin plastic sheet, a sliding window was employed and was manually opened after completion of the refrigerant discharge for each test.

A total of 47 Type K thermocouples were installed throughout the test room. The thermocouple response time was approximately 3 seconds. Six thermocouple arrays were placed with thermocouples at 4 in., 8 in., 12 in., and 18 in. (0.1, 0.2, 0.3, 0.46 m), above the floor and 4 in., 8 in., and 12 in. (0.1, 0.2, 0.3 m) below the ceiling. One thermocouple was placed at each of the release locations. Two thermocouples were placed near the floor at the simulated door opening. The test room humidity was measured with a handheld temperature and humidity combination unit. Temperature and humidity were monitored until the room conditions met the criteria to conduct a test. The pressure in the test room was monitored using an electronic differential pressure transducer with the range of 0 – 10 mm Hg. The pressure sensing port was located in the center of the room near the doorway. The leaked refrigerant gas concentration in the test room was measured by total hydrocarbon analyzers calibrated for the specific refrigerant of interest. The sampling ports were located 1, 12, 24 and 36 in. (0.025, 0.3, 0.6, 0.9 m) above the floor. There were eight high definition video cameras installed at different angles to document the test events. The ignition source used during the tests was electric arcs created by a step-up gas tube transformer. The electric arc transformer was continuously energized for several minutes during the tests. The location of thermocouples, electric arc igniters and refrigerant concentration sensors are shown in Figure 2.

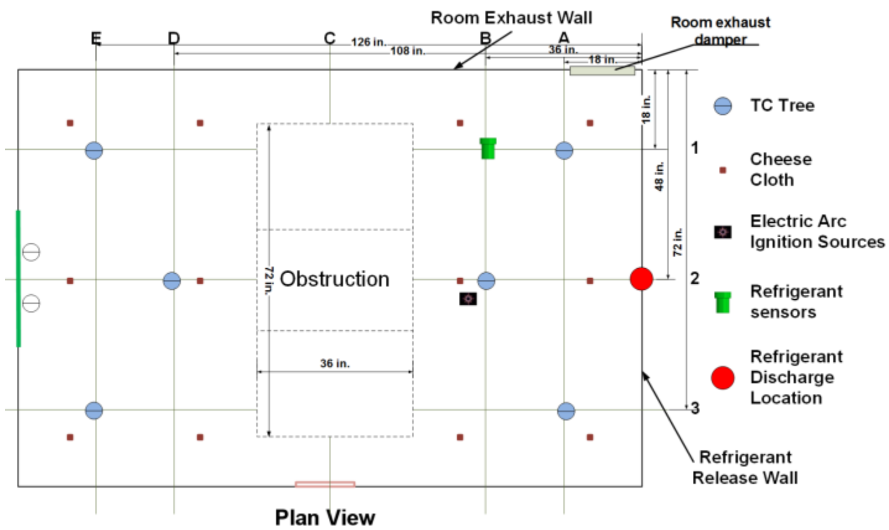

Figure 2: Task 1 test room setup and measurements (Gandhi et al, 2017)

The general procedure for testing was to initiate the data acquisition system 60 seconds prior to release of the refrigerant. When the target quantity of refrigerant was released with the target flow rate, refrigerant sampling through the refrigerant sensors was discontinued, and the sliding vent was opened (for tests using large venting size with sliding cover). Then electric arcs were initiated. The data were collected until all flaming had ceased for at least 2 minutes. At the end of a test sequence, the test room was exhausted through a smoke abatement system and replenished with fresh air.

2.2 Task 2: Scenario Testing in Whole Room-Scale

Task 2 included the scenarios that represented refrigeration and air conditioning scenarios. The refrigeration scenarios included a convenience store with reach-in cooler and a walk-in cooler inside a commercial kitchen. Air conditioning scenarios included (i) motel room with PTAC unit; (ii) residential basement with split air conditioning unit; and (iii) commercial kitchen with a rooftop unit. The residential scenarios considered the impact of refrigerant leak at the A-coil into the hallway and servicing error. Data were also developed on fire hazards from the failure of hermetic electrical pass-through component of a residential air-conditioning unit. Due to the page limit, only residential air-conditioner and reach-in cooler tests are illustrated here.

The refrigerant release methodology and the instrumentations in the scenario testing are similar to ISO room testing. In the scenario tests conducted, ignition sources were external to the air conditioning or refrigeration devices. The ignition sources used in the scenario tests included electric arc ignition sources (identical to those used in Task 1) and open flame sources consisting of tea candles (38.1 mm (1.5 inch) in diameter). The tea candles were lit manually prior to start of test for residential AC and reach-in cooler tests.

The reach-in cooler scenario simulated a product display refrigerator located in a convenience store. The test setup for the reach-in cooler is shown in Figure 3. The convenience store dimensions were 9.1x9.1x2.4 m (30x30x8 ft). Objects representing shelves were located in the test area. The reach-in cooler had outer dimensions of 69.6x82.6x202.2 cm (27.4 (w) x 32.5 (d) x 79.6 (h) inches) with an internal volume of 594.7 L (21 cu. Ft).

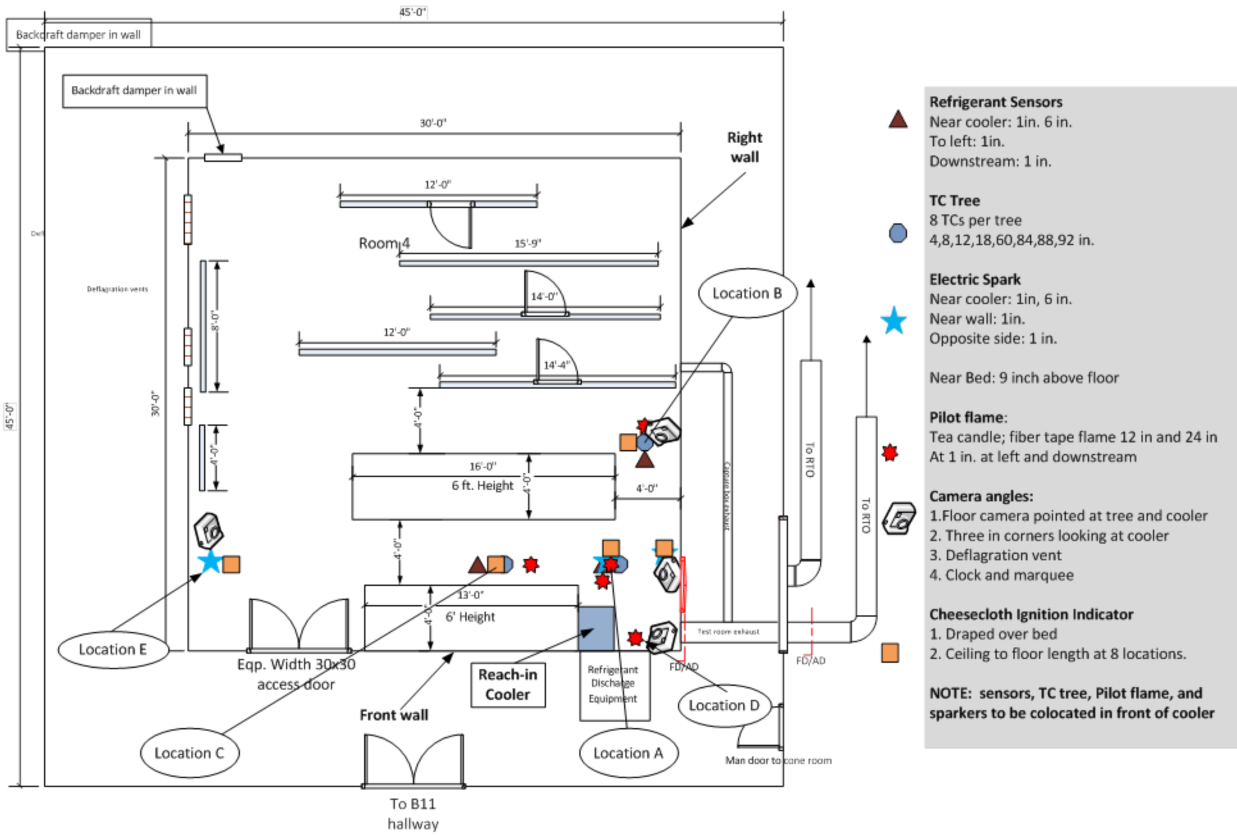

Figure 3: Task 2 Reach-in cooler test setup and measurements (Gandhi et al, 2017)

The refrigerant release rate was set to 10 g/s through a ¼ in copper tubing leading in to the top compartment of the reach-in cooler. The refrigerant release rate was selected so as not to blow the reach-in cooler door open during the release. The cooler bottom door was connected to a pneumatic device to remotely open the door when the refrigerant was completely released into the cabinet. The refrigerant release quantity was 500g as a starting point, as this is the current limit for class 2 flammable refrigerant in UL 471 edition 10 including revisions through November 2014 (UL, 2010).

The residential AC scenario simulated a ducted split air-conditioner for a 7.4x9.3x2.4 m (24 ft. - 2 in. x 30 ft. x 8-ft.) residential arrangement with the indoor air handler located in an 2.4x1.2x2.4 m (8x4x8 ft) utility closet. The test setup is shown in Figure 4. The test was configured to represent either a leak in the A-coil or a servicing error outside of the indoor unit. The air conditioning unit was ducted with return air from the bottom and conditioned air ducted to the hallway using a 40.6 cm (16 inch) duct. The closet had two return air grills at the bottom that were ducted to the air conditioning unit. The supply air duct was located at 2.2 m (7.2 ft) height.

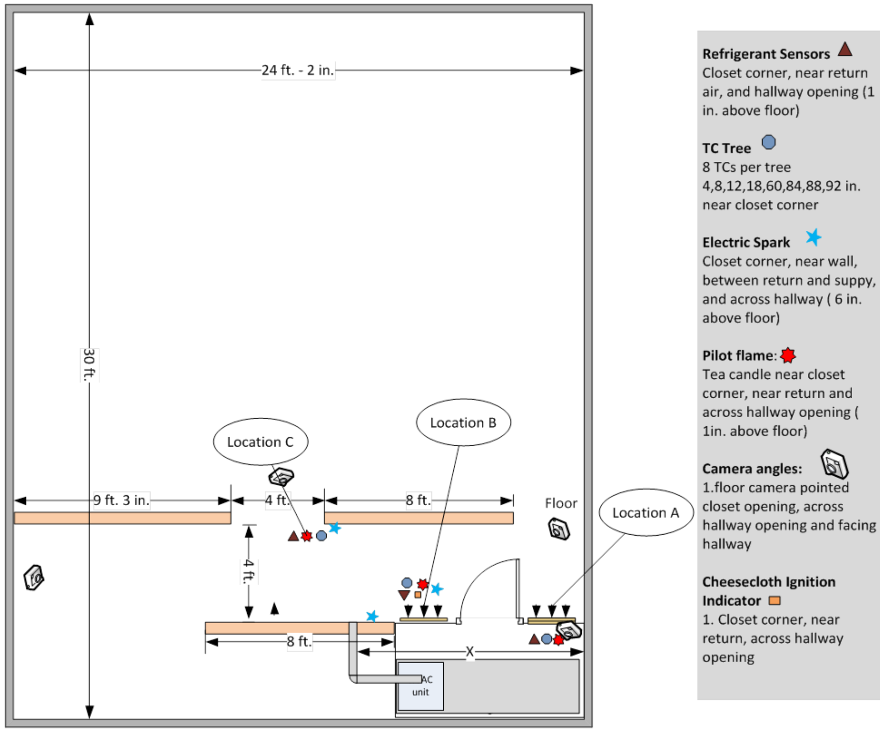

Figure 4: Task 2 Residential AC test setup and measurements (Gandhi et al, 2017)

Two charge levels were used for each tested refrigerant. First, the m1 charge per IEC 60335-2-40 edition 6 was selected for testing (IEC, 2018). This is the maximum allowable charge for which mitigation is not required for any type of equipment using A2Ls covered by the standard. Then, a higher charge level than m1 charge was tested following the defined mitigation requirement per the standard. The representative charge quantities for that size system and space were determined by making adjustments to the standard R-410A charge. According to manufacturers' input, a properly sized R-410A unit for the tested space typically needs 5.24 kg (11.55 lb) assuming installed with a 30.5 m (100 ft) line set. To achieve the comparable capacity, it was estimated that the R-32 and R-452B systems would have 27% and 20% charge reductions to the R-410A system respectively. Therefore, the charge quantities selected for testing were 3.83 kg (8.44 lb) for R-32 and 4.20kg (9.26 lb) for R-452B. The leakage in the A-coil scenario was conducted with refrigerant only (no oil) at a release rate of 50 g/s.

3. TEST RESULTS

3.1 Task 1: Parametric Testing in ISO Room

In Task 1, R410A and R22 with 1.5% and 3% lubricant by weight were tested to serve as our baseline. The refrigerants were released through a 25 mm tube at 0.2m above the floor with a target release rate of 100g/s (the actual release rates ranged from 75~99g/s). None of these tests resulted in the refrigerant and oil mixtures ignition.

Several factors that could affect A2L refrigerants ignition and event severity were investigated. The measured maximum ceiling temperature at 96 in. (2.4 m) above the floor and the maximum average ceiling temperature of all the measured locations at the 96 in. (2.4 m) above the floor were compared under different factors. The results are illustrated in Figure 5. These results were obtained at the release opening of 25 mm. The room pressure rise data were not presented here because the room vent was designed to avoid overpressure; however they were included in the project final report.

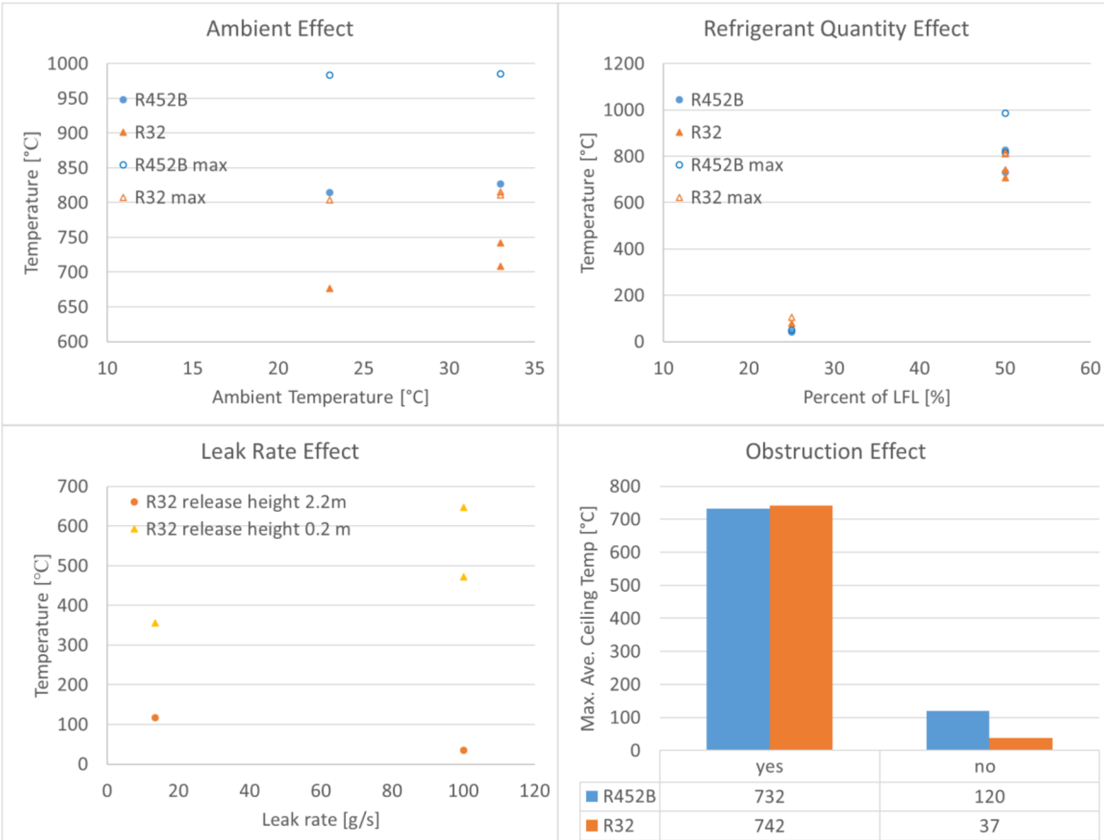

Figure 5: Examined factors that may affect the ignition severity

3.1.1 Ambient effect

Two ambient conditions were tested. One is representing normal room condition and the other is for hot and humid condition. The test numbers and conditions are shown in Table 1. The tests were conducted with pure refrigerants that were released at 0.2 meter above the floor.

Table 1: Test conditions for ambient effect testing

Test No.	**Refrigerant**	**Ambient (D.B./RH)**	**Whole Room Conc. (LFL%)**		**Discharge (kg)**	**Discharge Rate (g/s)**	
			Target	**Actual**		**Target**	**Actual**
PA01	R452B	73°F (23°C)/50%	50	61.7	3.82	100	98.9
PA02	R452B	91°F (33°C)/70%	50	60.7	3.76	100	97.4
PA03	R32	73°F (23°C)/50%	50	60.6	3.75	100	101.7
PA05	R32	91°F/(33°C)70%	50	60.6	3.75	100	96.8
PB01	R32	91/70%	50	62.8	3.89	100	82.0

The results show that the ambient conditions have minor or no effect to the overall event severity. Both R32 and R452B were ignited and the maximum temperatures were comparable for either case.

3.1.2 Refrigerant quantity effect

Two refrigerant charge levels were used in these tests. One is a quantity that results in refrigerant concentration that equals to 25% of refrigerant's lower flammability limit (LFL) when all the released refrigerant uniformly mixed with air inside the test room. Another level simply doubles the quantity and yields a concentration at 50% of refrigerant's LFL. The test conditions are listed in Table 2. The tests were conducted with pure refrigerants that were release at 0.2 meter above the floor. The room was maintained at 91°F (33°C) and 70% of RH.

All these tests resulted in refrigerant ignitions; however, the ignition events were significantly smaller at the lower charge. At the roughly 1.8 kg release amount, the ignitions for both refrigerants were mainly limited at the floor level; therefore their temperatures at ceiling level were much lower than those measured at the roughly 3.8 kg release level.

Table 2: Test conditions for refrigerant quantity effect testing

Test No.	Refrigerant	Whole Room Conc. (LFL%)		Discharge (kg)	Discharge Rate (g/s)	
		Target	Actual		Target	Actual
PA02	R452B	50	60.7	3.76	100	97.4
PB02	R452B	50	62.0	3.84	100	98.1
PB11	R452B	25	29.1	1.8	100	97.8
PA05	R32	50	60.6	3.75	100	96.8
PB01	R32	50	62.8	3.89	100	82.0
PB10	R32	25	28.6	1.77	100	96.1

3.1.3 Leak rate and leak height effect

This series was conducted using R32 without lubricant. The R32 was released at two different heights, representing floor level and ceiling level, and two release rates representing slow and fast leaks. The key parameters are shown in Table 3.

Table 3: Test conditions for leak rate and leak height effect testing

Test No.	Refrigerant	Discharge Height (m)	Discharge Rate (g/s)		Discharge (kg)	Whole Room Conc. (LFL%)	
			Target	Actual		Target	Actual
PA01	R32	2.2	13.5	13.6	3.26	50	52.7
PA02	R32	2.2	100	83.8	3.35	50	54.1
PA03	R32	0.2	13.5	13.8	3.25	50	52.5
PA05	R32	0.2	100	79.0	3.32	50	53.6
PB01	R32	0.2	100	81.6	3.34	50	53.9

The results demonstrated that the low leak location combined with a high leak rate resulted in more severe event compared to high leak location and low leak rate.

3.1.4 Obstruction effect

R32 and R452B were also tested when the obstruction in the test room was removed. The tests were conducted with pure refrigerants that were release at 0.2 meter above the floor. The room was maintained at 91°F (33°C) and 70% of RH.

Table 4: Test conditions for room obstruction effect testing

Test No.	Refrigerant	Obstruction	Whole Room Conc. (LFL%)		Discharge (kg)	Discharge Rate (g/s)	
			Target	Actual		Target	Actual
PA02	R452B	yes	50	60.7	3.76	100	97.4
PB02	R452B	yes	50	62.0	3.84	100	98.1
PB03	R452B	no	50	61.5	3.81	100	104
PA05	R32	yes	50	60.6	3.75	100	96.8
PB01	R32	yes	50	62.8	3.89	100	82.0
PB12	R32	no	50	56.4	3.49	100	98.7

All these tests with obstruction resulted in refrigerant ignitions. The ignition events were larger when the obstruction was present. When the obstruction was removed, the ignition for R452B was mainly limited at the floor level, and no flame was formed for R32 (only small blue corona was at ignition sources; therefore their temperatures at ceiling level were much lower.

3.2 Task 2: Scenario Tests in Whole Room Scale

Due to the page limit, only residential air-conditioner and reach-in cooler tests are illustrated here. The remaining results are detailed in the project report (Gandhi et al, 2017). Readers are encouraged to read the project final report.

3.2.1 Residential air conditioner

The key parameters are listed in Table 5. Refrigerants R32 and R452B were tested under two charge levels: the maximum charge that does not require mitigation per IEC 60335-2-40 (Res04 and Res 05) and a typical charge level scaled from a typical R410A system for the size of the test room (Res02 and Res03), respectively. All four tests resulted in refrigerant ignition in the hallway in around 12 seconds in proximity to the return grill where candle flame and electric arc sources were located. Figure 6 shows the maximum temperatures at the ceiling level and near the floor. The highest temperatures occurred between 4 and 12 inches above the floor.

For the tests that have no fan circulation, the flaming was of longer duration in the hallway even though the refrigerant release charge was smaller when compared to the tests in which the fan was turned on to circulate the air in the test room. However, the flames were drawn into the indoor unit through the return grill and flaming was observed within the unit when the fan was turned on.

Table 5: Test conditions for residential split unit testing

Test No.	**Refrigerant**	**Discharge (kg)**		**Discharge Rate (g/s)**		**Fan Mitigation**	**Result**
		Target	Actual	Target	Actual		
Res02	R32	3.83	3.91	50	47.1	30s delay	Ignition
Res03	R452B	4.20	4.27	50	47.4	30s delay	Ignition
Res04	R32	1.80	1.82	50	46.4	No	Ignition
Res05	R452B	1.85	1.87	50	46.3	No	Ignition

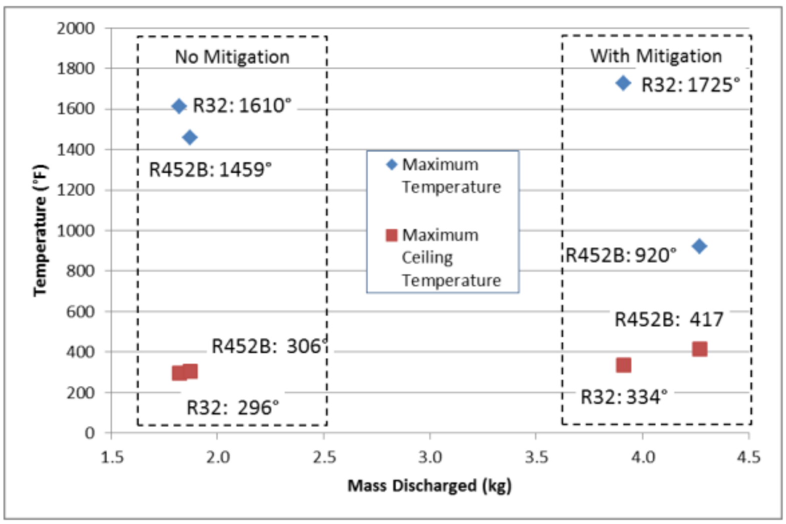

Figure 6: Measured temperatures in residential split unit testing (Gandhi et al, 2017)

3.2.2 Commercial reach-in cooler

For reach-in cooler tests, the first two tests were for R455A and R457A at a target of 500g charge level which is the current limit for class 2 flammable refrigerant in UL 471 (UL, 2010). Ignition occurred for both tests. In addition, R457A showed a quicker reaction than R455A. Higher temperatures were observed for R457A. The remaining two tests were conducted using only R457A at 300g and 400g respectively. At 300g level, the burning candles showed some flaring due to the presence of the refrigerant, but no visible spread of flame into the surrounding air. The ignition was observed at the 400g charge level but with a less severity than the test at 500g level. In those cases where ignition occurred, the highest temperatures attained were near the floor level. Figure 7 shows that temperatures from the events increased with increasing charge size. R-455A with a release of 600 grams showed lower temperatures than R-457A with a release mass of 500 grams.

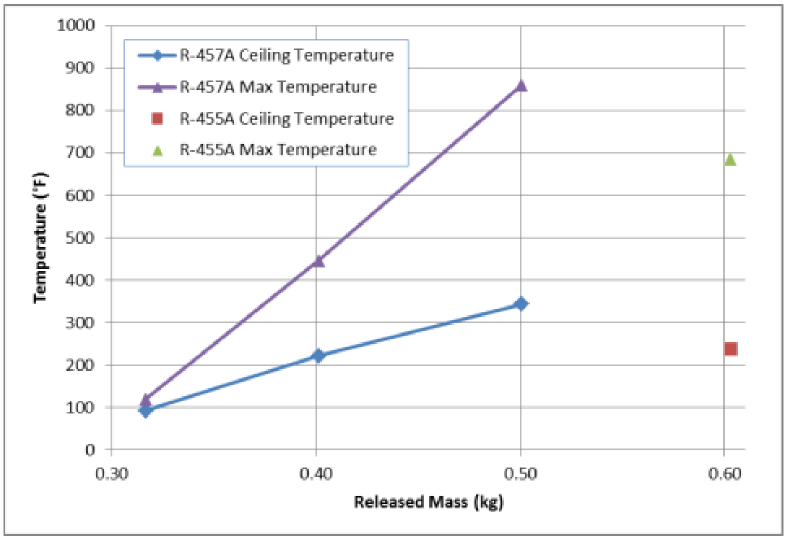

Figure 7: Measured temperatures in reach-in cooler testing (Gandhi et al, 2017)

Table 6: Test conditions for reach-in cooler testing

Test No.	Refrigerant	Discharge (kg)		Discharge Rate (g/s)		Result
		Target	Actual	Target	Actual	
Cooloer01	R455A	0.50	0.60	10	6.1	Ignition
Cooloer02	R457A	0.50	0.50	10	9.0	Ignition
Cooloer03	R457A	0.30	0.32	10	4.1	No Ignition
Cooloer04	R457A	0.40	0.40	10	5.0	Ignition

4. DISCUSSION

It must be stressed that the testing was more focused on understanding the ignition event severity, rather than the probability of the refrigerant ignition event. Some tested ignition events represented the scenarios with low probability of occurrence. For instance, ignition sources used in the testing had sufficient energy (i.e., much greater than the minimum ignition energy) to cause ignition of a flammable mixture. In addition, ignition sources were located where combustible mixtures were most likely to occur. Therefore, some relatively low probability events were forced to occur. Due to the limited resources, only typical equipment and setup were tested. Care must be exercised when attempting to make broad conclusions because small statistical sample sizes were used for most tests.

In the testing, thermocouples were used to measure temperatures; however, their readings do not reflect actual flame temperatures. The instantaneous temperatures of the flames are higher than what the thermocouples recorded because thermocouples have response time delay, and the flames have fast movements. This may create a difficult time when the measured temperatures are used to validate modeling simulations; however, the relative values and trends among different scenarios do reflect the different severity levels for tested scenarios.

The test room pressure rise data were not presented in this paper; however they were included in the project final report. It should be noted that these pressure rise measurement does not reflect the actual pressure change inside a room in real world situation because the test room was intentionally equipped with a large vent designed to avoid overpressure. In reality, the pressure rise would be much higher than what was measured due to limited venting area in a real room.

In the residential air-conditioner hallway tests, two tests simulated the use of refrigerant sensor and indoor blower as a means to mitigate the ignition risk. The response time of a sensor detecting a leak and energizing the indoor blower to circulate the air was assumed to be 30 seconds. However, sensor response times may be much quicker in reality.

5. CONCLUSIONS

The testing provided the following key learnings:

- Room temperature and humidity had little to no effect to event severity.
- Refrigerant concentration, leak rate and release height influence event severity.
- R-410A (with oil) did not ignite under any circumstances
- There were no major differences between R-452B and R-32. R-457A reacted more quickly than R-455A.
- When liquid refrigerants rapidly escape from systems, it is possible that they will not fully vaporize and thus will create liquid refrigerant pooling and lingering longer than expected because of the self-cooling effect.
- For reach-in cooler, refrigerant charge size matters (even just 100 gram difference reduced the ignition and propagation event).
- For residential air-conditioner hallway tests, the indoor blower must activate quickly to dilute the flammable mixture and avoid ignition as an effective mitigation means.

The testing was more focused on understanding the ignition event severity, rather than the probability of the refrigerant ignition event. The future work should include characterization of refrigerant leak scenarios with actual equipment in "on" and "off" states, and real world ignition sources in terms of ignition energy, quantity, spatial location throughout the room, and activation frequency.

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ACKNOWLEDGEMENT

The project was strongly desired and supported by the HVACR industry. A group of industry experts provide technical guidance and products for testing. AHRI is grateful to all of them for contributing their expertise and resources to the project.