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A3 Refrigerant R290 Leak and Ignition Testing for a Packaged Terminal Air-conditioner (PTAC)

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Abstract

R290 (propane) is a flammable refrigerant having an A3 classification according to the ASHRAE Standard 34. Because of its extremely low Global Warming Potential (GWP), several regions around the world use or consider using it for air-conditioning and refrigeration applications. On the other hand, the R290 application is currently limited to small charged self-contained air-conditioning and refrigeration products in most of the world due to its high flammability and safety implications. The possibility of increasing R290 charge limits set by relevant safety standards (IEC/UL-60335-2-40 and IEC/UL-60335-2-89) is being evaluated in the working groups of these standards.

To properly address A3 refrigerants in safety standards, the Air-Conditioning, Heating, and Refrigeration Technology Institute (AHRTI) undertook a research project to investigate R290, specifically to carry-out leak and ignition testing under whole room scale conditions.

This paper summarizes the results of A3 refrigerant R290 leak and ignition tests for a packaged terminal air-conditioner (PTAC). A mock-up full scale motel room was built with a wall mounted PTAC installed. The testing simulated refrigerant leaks from the evaporator with ignition sources present. Two different R290 charge levels (114g and 217g) were tested. The tests also included using the PTAC circulation fan to disperse leaked refrigerant in the test room as a mitigation method. The tests demonstrated that the ignition severity depended on the charge level and the fan operating state. In all ignition events observed, the highest temperatures were recorded close to floor level indicating flames were low in height. The results were also compared to existing test results of A2L refrigerants R32 and R452B under the same test setup.

Keywords: Low GWP, refrigerant, flammability

1. Introduction

The global industry is transitioning to environmentally friendly low global warming potential (GWP) refrigerants. To date, most of promising low GWP refrigerants are flammable. Implementation of these refrigerants in the field requires revisions of relevant safety standards and codes. To advance the understanding of flammable refrigerants safety, AHRTI launched a research project to conduct whole room scale testing. The objective was to conduct refrigerant leak and ignition testing under whole room conditions to understand the potential ignition and event severity associated with the use of A2L and A3 refrigerants [1, 2]. The whole room testing was conducted by AHRTI's contractor UL at its test facility in Northbrook, IL.

The overall testing consisted of scenarios that represented refrigeration and air conditioning applications. The refrigeration applications included reach-in coolers testing. Air conditioning scenarios included (i) motel

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room with PTAC unit; (ii) motel room with mini-split unit. For simplicity, this paper provides a high-level summary of the PTAC tests. More detailed information is contained in the project final reports [1, 2].

2. Test Setup and Procedures

Refrigerants R290, R32 and R452B were tested for the PTAC. Their information is listed in Table 1. One can observe that R290 has significantly lower LFL than the two. Therefore, its allowable charge amount is much less than A2Ls.

Table 1. Refrigerant properties

Parameter	R290	R32	R452B
Safety Classification per ASHRAE Standard 34 [3]	A3	A2L	A2L
Lower Flammability Limit (LFL, % volume)	2.1%	14.4%	11.9%
Lower Flammability Limit (LFL) kg/m³ at 101.3 kPa	0.038	0.307	0.310
Upper Flammability Limit (UFL, % volume)	9.5%	29.3%	22%
Laminar Burning Velocity (cm/s)	44	6.7	<4.0
Composition (% mass)	R290 (100%)	R32 (100%)	R32/R1234yf/R125 (67%/26%/7%)

A full scale motel room was built to simulate real application. To avoid over-pressure and damage to the test room from ignition events, six deflagration vents were created at the top section of two walls. Four of them had dimensions of 0.6m x 1.2m (2ft. x 4ft.), and two had dimensions of 0.6m x 0.9m (2ft. x 3ft.). They were covered by plastic sheets. The plastic sheets provided air seal environment inside the test room and could be blown or melted open due to pressure/temperature rise should an ignition event occur.

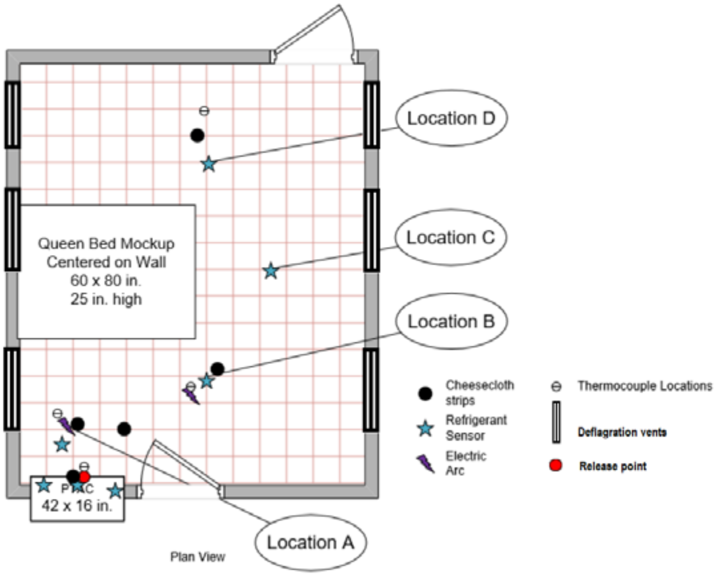


Fig. 1. Schematic of test room setup and instrumentation plan [2]

The plan view of the test setup is shown in Figure 1. The room dimensions were 3.95m x 4.81m x 2.42m (13ft. x 15ft. 9in. x 7ft. 11in.). The enclosed volume was 46.0 m³ (1620 ft³). The floor area was 19.0 m² (205 ft²). A mockup bed was located in the room. A PTAC was mounted such that the base of the unit was 0.4 m (16 inches) above the floor at the minimum distance from the side wall. An 8mm (¼ inch) O.D. copper tube was placed in the center of the evaporator coil at 0.6 m (24 inches) above the floor. The tube was angled directly out from the face of the evaporator towards the front grill as shown in Figure 2. When used, the unit fan was operated on low speed. The fan volume flow rate was determined to be 5.7 m^3/min (200 CFM). The measurements were made with a calibrated vane anemometer at several locations across the exhaust outlet and integrated with area to determine volume flow rate.

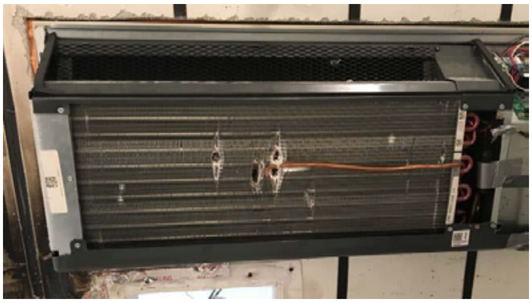


Fig. 2. PTAC discharge tube location [2]

The locations of the instrumentation, and ignition sources were located in clusters at locations A, B, C and D shown in Figure 1. These locations were chosen according to the expected refrigerant flow path. The leaked refrigerant gas concentration in the test room was measured by oxygen sensors (Apogee SO-220 electrochemical sensor). High speed video cameras installed at different angles to document the test events. Cheesecloth strips were used to indicate whether the refrigerant ignition would cause a secondary fire. A total of 32 Type K thermocouples were used to measure the temperature at different locations and heights within the room. The thermocouple response time was approximately 3 seconds. 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.

During the test, the refrigerant in liquid phase was released into test room with several viable ignition sources present. The refrigerant release system is illustrated in Figure 3. 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 R290 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. The solenoid valve was used to start and stop the refrigerant flow during testing.

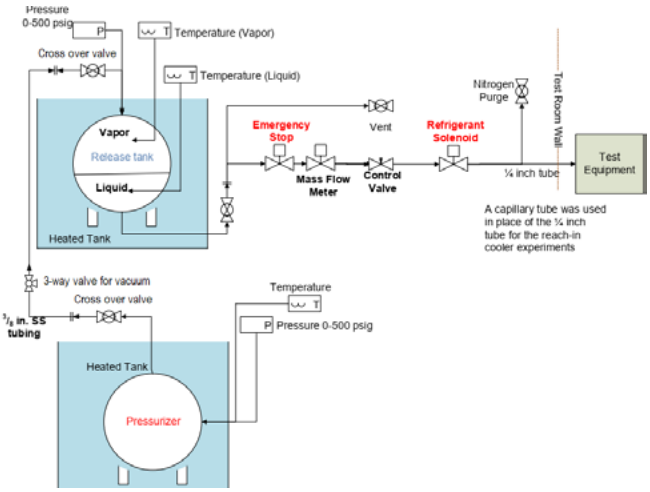


Fig. 3. Schematic of the refrigerant release mechanism setup [2]

The ignition sources used in the scenario tests are electric arcs. The electric arcs were created by a step-up gas tube transformer. The electric arc transformer was continuously energized for several minutes during the tests. The energy of the electric arc in one-half 60 Hz cycle was 0.147 joules (147 mJ). This ignition energy is nearly 300 times the commonly accepted minimum ignition energy of propane/air mixtures at 0.46 mJ [2].

The general procedure for testing was to get the refrigerant release system ready, initiate the data acquisition prior to release of the refrigerant, discharge the target quantity of refrigerant at the target flow rate, and energize the electric arcs at 5 seconds after the completion of the discharge.

The R290 test matrix is shown in Table 2. Two tests were conducted with the circulating fan off. One test was planned with the fan running before the discharge began.

Table 2. R290 test matrix

Fan State	Planned Discharge (g)	Planned Discharge Rate (g/s)
Off	114g	21.4
Off	217g	21.4
On	217g	21.4

The R290 charge levels used in the testing had their bases in either existing or proposed limits for A3 refrigerants. In the absence of recommended limits for A3 refrigerants, the formulas for A2L refrigerants were used on the assumption that limits for A3's would follow the same formula. This approach allowed the project to assess safety factors for refrigerant charge quantity and mitigation criteria including mitigation response time and airflow rate for mixing and threshold for performing a certain safety test for commercial refrigerators. Table 3 and the notes below the table contain the determination of the charge limits used in this test series. The R290 discharge rate was based on the finding that the mass flow rate of liquid propane is 49% of the R-32 liquid mass flow rate at the same saturation temperature and orifice size [2]. The value was selected so that comparisons are possible between the A2L and propane refrigerant tests in the 9007-01 [1] and 9007-02 [2] programs.

Table 3. PTAC Charge Limit Determination [2]

Charge Limit	A3 (R290)	A2Ls	Mitigation Requirement
m_1 per UL 60335 2-40 Nov 2017	$3 \times LFL$ (114g)	$6 \times LFL$ (R-32: 1.81kg, R-452B: 1.85kg)	No mitigation required
m_1 per IEC 60335 2-40 Edition 6	$4 \times LFL$ (152g)		
m_{max} per UL 60335 2-40 Nov 2017	217g (notes 1,3)	$0.5 \times LFL \times h_a \times A$	Air circulation
m_{max} per IEC 60335 2-40 Edition 6	325g (notes 2, 3, 4)	$0.75 \times LFL \times h_a \times A$	Air circulation

Notes:

1. Nov. 2017 draft of UL 60335-2-40 [4]: $m_{max} = 0.5 \cdot LFL \cdot h_a \cdot A = 217g$
2. IEC 60335-2-40 Edition 6 [5]: $m_{max} = 0.75 \cdot LFL \cdot h_a \cdot A = 325g$
3. Using A2L equations for A3. A3 equations in development.
4. 325g not tested because 217g ignited with air circulation

3. Test Results [1, 2]

The PTAC ignition tests are summarized in Table 4. Three ignition tests (PTAC_14, 16 and 17) were performed following the plan outlined in Table 2. In PTAC_15 test, the electric arcs were energized ~1 s instead of planned 5 s after completion of the discharge. This test was repeated as PTAC_16. While PTAC_15 was incorrect in its procedure, the largest number of deflagration vents were burst in this test due to the higher concentrations existing immediately after completion of the discharge.

R290 tests all resulted in ignition even in the case that the fan was running continuously before the start of the discharge of 217g R290. The severity depended on the charge level. Without fan running, the highest temperatures were recorded close to floor level indicating flames were low in height (C-08, 8 inch above floor at location C). With the fan running, the highest temperature was measured at 60 inches above the floor at location B (B-60). Temperatures at the ceiling level were due to buoyant transport and not direct flame impingement. Temperatures and refrigerant concentrations over time at measured locations were not presented in this paper for simplicity. Readers are encouraged to read the report for details. Since all three planned tests resulted in ignition, testing at higher charge level was terminated.

Table 4. PTAC R290 ignition test results

Test Code	Fan State	Measured Discharge (g)	Measured Discharge Rate (g/s)	Max Temp (°C)	Max Temp Location	Max Ceiling Temp (°C)	Number of Vents Burst /Melted	Arc Delay Time (s)
PTAC_14	Off	214	18.3	463	C-08	216	3/3	4.3
PTAC_15	Off	111	20.9	534	C-08	277	4/1	0.9
PTAC_16	Off	110	20.4	371	C-08	99	2/1	5.7
PTAC_17	On (200cfm)	215	20.4	383	B-60	117	3/1	5.7

Estimates for the maximum flame size were made from the videos and are shown in Figure 4. The photos demonstrate the effect of timing the electric arcs. PTAC_15 was an invalid test and the comparison to PTAC_16 shows the effect of early ignition before the propane was able to mix and diffuse. PTAC_15 is considered an invalid test because its igniter timing was too short compared to the test plan, but still contains informative data about ignition timing. Comparison of PTAC_14 (Fan off) and PTAC_17 (Fan ON) both with 217 g discharges shows a small effect from the action of the fan in reducing the size of the flames. PTAC_17 (Fan on) resulted in bursting three deflagration vents compared to two bursts in the PTAC_14 test (Fan off)

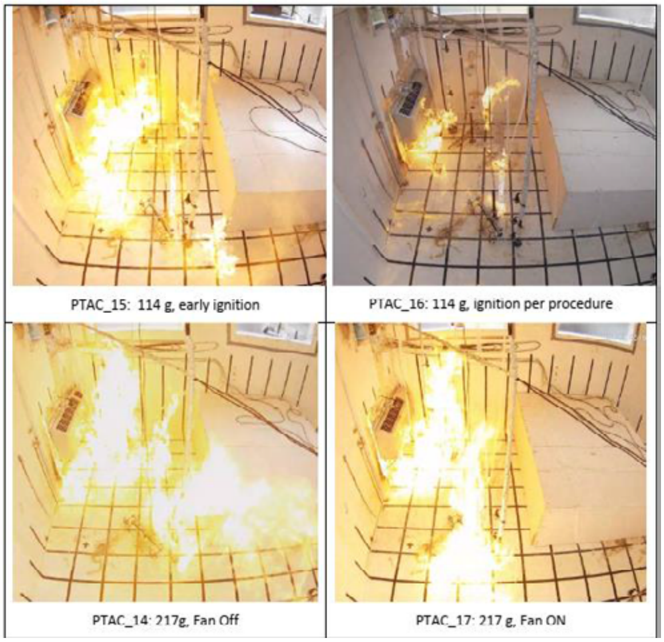
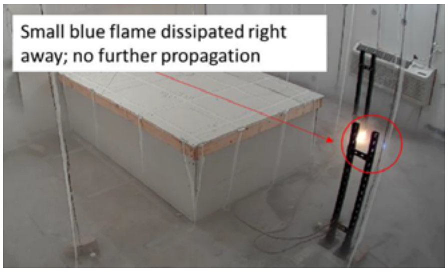


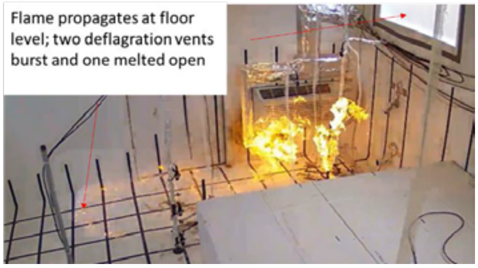
Fig. 4. PTAC Estimated maximum flame sizes

For comparison purpose, Figure 5 shows test results for both A2L refrigerant R452B and A3 refrigerant R290 using UL-60335-2-40 m1 charge level specified in Table 3. The R290 test parameters were listed as PTAC_16 in Table 4. The R452B test was conducted under the same room dimension and similar test procedure. 1.9 kg of R452B was actually released during the test (the target amount was 1.85kg). The R452B release rate was ~47g/s due to the density difference from R290 as noted before. The ignition source and ignition timing used for R452B test were also different from the R290 test. The ignition sources were electric arcs (same as R290 tests) with tea candles.

For R452B test, the ignition sources were energized approximately 27 second after the completion of the release. A small refrigerant flame was observed near location A (in front of the PTAC). The flame was quickly distinguished with no further propagation. The total flaming time for the refrigerant flame was 3 seconds. The cheesecloth was not ignited. The same test was performed using A2L refrigerant R32 at around 1.8kg with same release rate as R452B. The ignition sources were energized approximately 15 second after the completion of the R32 release. No ignition was observed. For R290 PTAC_16 test, the flame propagated along the floor indicating a flammable region had formed at the floor level.



(a)R452B, 1.9 kg, 47.4 g/s, no mitigation



(b)R290, 110 grams, 21 g/s, no mitigation

Fig. 5. PTAC Test R452B vs R290

4. Discussion

The PTAC testing was designed to assess the R290 charge levels according to the then current proposed "Preliminary Comment Draft" of 3rd Edition UL 60335-2-40 (dated Nov 22, 2017) which was based on the 6th Edition of IEC 60335-2-40. According to the draft UL 60335-2-40, the charge limit for R290 is 114g regardless the room size for direct systems; however, the IEC standard 60335-2-40 Edition 6.0 allows higher charge. The IEC standard allows R290 charge up to 152g without room size restriction. Charge higher than 152g is correlated to the room area and equipment installation height for an unventilated room.

The PTAC AC tests indicated that the flammable cloud can form at floor level and be ignited at the current charge limit of 114g without room size restriction defined in UL 60335-2-40. The testing also demonstrated that the maximum allowable charge (325g) per the test room area (19m2) calculated using IEC 60335-2-40 would have caused R290 to build up flammable region around the unit vicinity at floor level and caused ignition when the ignition sources were present.

Both IEC and UL 60335-2-40 specify requirements for equipment using A2L refrigerants with incorporated circulation airflow which includes an incorporated fan to be either continuously operated or initiated by a refrigerant detection system. This concept is to ensure circulation airflow prevents refrigerant stagnation so that the equipment can use higher refrigerant charge than those without this feature. At present, neither the IEC nor UL 60335-2-40 has specified such requirements for A3 refrigerants that would allow higher A3 refrigerant charge quantity. IEC has established a WG (SC61D/WG16) to develop additional requirements for A3 refrigerants including the incorporated airflow concept. This project used the existing requirements for A2Ls in terms of determining charge quantity, minimum airflow rate for R290 tests to assess these requirements applicability to A3 refrigerants. The PTAC testing demonstrated that ignition can even happen while the PTAC fan is kept constantly on at low speed setting during the refrigerant release. This indicates that 1) the safety factor in the calculation of refrigerant quantity may not be enough; and 2) the mitigation using air flow may require a higher air flow rate than the A2L refrigerants to mitigate A3 refrigerants for floor mounted products.

The test results demonstrated that R290 was much easier to be ignited, and the ignition events were more severe compared to A2L refrigerants R32 and R452B at m1 charge level.

It should be stressed that testing scenarios were designed according to the existing requirements or proposed requirements in the IEC Standards 60335-2-40 and its equivalent North American version UL 60335-2-40. However, the R290 discharge rates were based on the finding that the mass flow rate of liquid propane is 49% of the R-32 liquid mass flow rate at the same saturation temperature and orifice size [2]. These values were selected so that comparisons are possible between the A2L and propane refrigerant tests in the 9007-01 [1] and 9007-02 [2] programs. As with the 9007-01 program, leak rates were almost always higher than the rate corresponding to total loss of charge in four minutes that was generally considered by the IEC/UL 60335-2-40. Generally speaking, this means the scenarios are more severe than they would have been with four minute leaks.

5. Summary

The PTAC testing generated a set of R290 dispersion and ignition data at different release amounts. The results provide useful information to product safety standard IEC/UL 60335-2-40. According to the testing, the following findings are recommended to the IEC/UL 60335-2-40 committee for consideration:

- Raising the current m1 (114g for R290) charge limit per UL 60335-2-40 should be carefully considered especially for floor or near floor mounted products.
- Any potential ignition sources should be avoided underneath installed units and near the projected area at floor level
- Air flow requirements as a mitigation method should be carefully considered in relation to the amount of refrigerant, and perhaps type of refrigerant (A2L's vs A3's).

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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