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AHRI's Research on Rooftop Packaged Heat Pumps

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Abstract

This paper provides an overview of the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) research activities on air-conditioners and heat pumps. During the past few years, AHRI conducted research projects covering low Global Warming Potential (GWP) refrigerants testing and risk assessment of mildly flammable refrigerants of packaged rooftop units (RTUs).

Several low-GWP alternative refrigerants were tested for RTUs in air-conditioning and heat pump applications and other type of heat pumps in the AHRI Low-GWP Alternative Refrigerants Evaluation Program (Low-GWP AREP). Summarized testing results are presented in this paper. Many of the tested refrigerant candidates to replace R-410A are classified as A2L according to ASHRAE Standard 34. This paper will also summarize AHRI's study on risk assessment of RTUs using A2L flammable refrigerants. The potential ignition risks of R-32 and HFO-1234yf in RTUs during operation and servicing were analyzed. The risk scenarios include 15-ton RTU for commercial kitchen, 25-ton RTU for office building, and 5-ton packaged unit installed on the ground for office building. CFD simulation on refrigerant leaks in various situations and fault-tree analysis on the refrigerant ignition risk are summarized. The risks due to refrigerant release and ignition are far below risks of other common hazards.

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1. Introduction

The Air-Conditioning, Heating, and Refrigeration Institute (AHRI) is a trade association representing manufacturers of HVACR and water heating equipment within the global industry. For almost three decades, these manufacturers have provided leadership by sponsoring cooperative, pre-competitive research in the HVACR, water heating and building sectors. Over the past few years, AHRI has conducted two major heat pump and refrigerant related research projects, including heat pump performance testing using low Global Warming Potential (GWP) refrigerants and risk assessment of RTUs using mildly flammable refrigerants. These projects were conducted by companies and contractors participating in AHRI's research activities either voluntarily or under AHRI research contracts. This paper is a high level summary of their work. More detailed information is contained in individual reports listed in the reference section of the paper.

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2. Heat Pump Performance for Low-GWP Refrigerants

AHRI led an industry-wide cooperative research program, the Low Global Warming Potential Alternative Refrigerants Evaluation Program (Low-GWP AREP) over the past five years. The program aimed at identifying and evaluating promising low-GWP alternative refrigerants for major air conditioning and refrigeration products. The program did not prioritize these alternatives; rather, it identified potential replacements for high GWP refrigerants, and presents the performance of these replacements in a consistent and standard manner. Phase I testing of the program was completed at the end of 2013 and produced 40 test reports [1]. Phase II testing started in 2014, and produced 33 test reports [2]. Phase II reports included compressor calorimeter testing, system drop-in testing, and soft-optimized system testing.

Seven heat pumps, including air-source and water-source types, were tested with different low-GWP refrigerants. Information on these tested refrigerants and their baseline is summarized in Table 1. The tested heat pumps and types of tests are summarized in Table 2. Two types of testing were conducted: drop-in and soft-optimized. The drop-in tests were conducted with the alternative refrigerants placed in heat pumps using baseline refrigerant R-410A or R-407C with only minor modifications, if any, made to the equipment (e.g. adjusting charges or TXV settings). The soft-optimized tests were performed by using a variable speed compressor to simulate different compressor size [1, 2].

Table 1: Low-GWP refrigerants tested for heat pump application

Baseline	Refrigerant	Composition	(Mass%)	Classification (Note 1)	GWP ₁₀₀ (Note 2)
R-407C	R-290	R-290	100	A3	<5
	DR-3	R-32/R-1234yf	21.5/78.5	A2L	148
	L-20a (R-444B)	R-32/R-1234ze/R-152a	41.5/48.5/10	A2L	295
	ARM-71a	R-32/R-1234yf/R-1234ze(E)	68/26/6	A2L	460
R410A	DR-5A (R-454B)	R-32/R-1234yf	68.9/31.1	A2L	466
	DR-55 (R-452B)	R-32/R-125/R-1234yf	67/7/26	A2L	698
	HPR2A	R-32/134a/1234ze(E)	76/6/18	A2L	600
	L-41-1 (R-446A)	R-32/R-1234ze/Butane	68/29/3	A2L	461
	L-41-2 (R-447A)	R-32/R-1234ze/R-125	68/28.5/3.5	A2L	583

Notes:
 1. Refrigerants' classifications or intended classifications according to the ASHRAE Standard 34 [3].
 2. GWP values are calculated based on IPCC AR-4 100 year.

Table 2: Summary of tested heat pumps and tests conducted

Unit No.	Equipment Type	Baseline Refrigerant	Refrigerants Tested	Test type	Test Standard	AREP Report No.
1	3-ton air source, split	R-410A	ARM-71a, DR-5A, HPR2A, L-41-1, L-41-2	drop-in	AHRI Standard 210/240	52 [4] (Burns, et al, 2015)
2	3-ton air source, split	R-410A	R-32, DR-5A	drop-in	AHRI Standard 210/240	54 [5](Stöben et al, 2015)
3	4-ton air source, rooftop packaged unit	R-410A	R-32, DR-5A, DR-55	soft-optimization	AHRI Standard 210/240	63 [6](Schultz et al., 2015 and 2016)
4	1-ton water-to-water, heat pump	R-410A	R-32, L-41-1, L-41-2	drop-in	ISO Standard 13256-2 and EN Standard 14511-2	43 [7](Park et al., 2015)
5	1-ton, single packaged vertical heat pump (SPVH)	R-410A	R-32	drop-in	AHRI Standard 390	44 [8](Wuesthoff et al, 2015)
6	3-ton water-to-air, heat pump	R-410A	R-32, DR-5A, DR-55, L-41-2	drop-in and soft-optimization	ISO Standard 13256-1	60 [9](Brown et al., 2016)
7	4.5-ton air-to-water heat pump	R-407C	DR-3, L-20a, R-290	drop-in	EN Standards 14511 and 14825	61 [10](Stöben et al, 2016)

Test results for all seven heat pumps can be found in the Low-GWP AREP Test Reports listed in the reference section. The tested systems’ heating capacity and coefficient of performance (COP) for alternative refrigerants and baseline R-410A were measured and compared. Using Units 1~3 as an example [4-6], a rooftop packaged heat pump and two split system heat pumps were tested at H1 and H3 conditions in Table 3 per AHRI Standard 210/240 [11]. The alternative refrigerants relative heating performance to the baseline R-410A is shown in Figure 1 (a) and (b) respectively.

Table 3: Test conditions per AHRI Standard 210/240 [11]

	Air Entering Indoor Unit Temperature [°C]		Air Entering Outdoor Unit Temperature [°C]	
	Dry Bulb	Wet Bulb	Dry Bulb	Wet Bulb
H1 Steady State Test	21.1	15.6	8.3	6.1
H3 Steady State Test	21.1	15.6	-8.3	-9.4

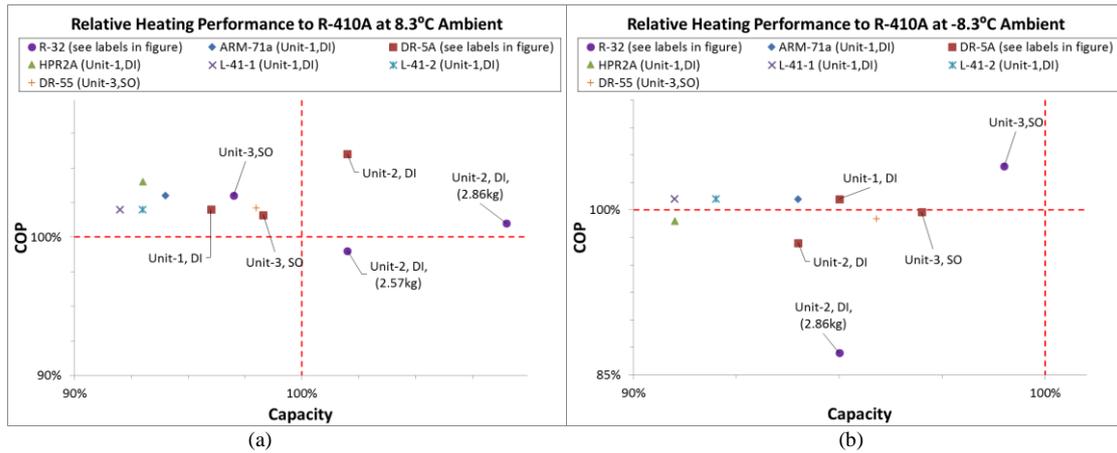


Fig. 1. Relative Performance of the Tested Air-source Heat Pumps

R32 and DR-5A were tested in all three units from different manufacturers. Figure 1 generally shows that these low GWP refrigerants showed comparable or better COP, but some showed lower capacity than R-410A, especially for the H3 condition. It should be noted that these results are not necessarily the optimum performance of the low GWP refrigerants as the units’ charge quantities were determined for cooling mode. Cautions should be used when analyzing the data. It should be stressed that the capacity and efficiency are not strictly comparable among refrigerants when their suction vapor densities are different in drop-in testing, and when different test companies use different drop-in or soft-optimization procedures [2]. The test procedure and results must be interpreted to account for charge quantity, expansion device, and/or compressor speed adjustment [2]. A brief summary of these variations is listed in Table 4.

Table 4. Summary of testing variations [12]

Unit No.	Expansion Valve	Lubricant	Compressor	Charging procedure
Unit-1	fixed orifice	same POE	same	TXV was used to adjust superheat and charge level was adjusted to match subcooling at cooling “B” condition.
Unit-2	same TXV	same POE	same	use same charge initially, then R32 charge was optimized to match subcooling in cooling mode
Unit-3	adjustable TXV	same POE	speed varies to match capacity (410A and DR55 at 60Hz, DR5A at 61Hz, R32 at 55Hz)	the optimum charge was selected to maximize unit efficiency at cooling “A” condition while also matching the subcooling. The TXV was adjusted to match compressor suction superheat in heating mode.

All three heat pumps’ charge quantities were determined when matching either the subcooling or superheat (or both) in the cooling mode with or without the expansion devices adjustment. Consequently, different results may be obtained, and premature conclusions could be drawn if readers do not understand the source of variations [2]. For example, R-32 was originally tested in Unit 2 in Figure 1 with the same charge quantity (2.86 kg) as the R-410A. The excessive amount of subcooling was observed in cooling mode suggesting that the system may be over-charged. The R-32 charge amount was reduced to 90% of the original charge (2.57 kg) in cooling mode to improve

the cooling performance. However, the heating performance with this reduced charge quantity was significantly degraded. Around 25% of capacity and COP decrease was observed at H3 condition. It is clearly shown that there was an optimum charge quantity discrepancy between the cooling and heating modes. A simple variation of the charge could lead to relative performance changes.

3. Risk Assessment of A2L Refrigerants in Commercial Rooftop Units

In the Low-GWP AREP, majority of evaluated low GWP refrigerant candidates are classified as A2L according to ASHRAE Standard 34 [3]. These refrigerants have low burning velocity and are mildly flammable. AHRI recently completed a research project employing Fault Tree Analysis (FTA) to assess the ignition risks of using A2L refrigerants in commercial RTUs [13]. The scope of the risk assessment was to evaluate the refrigerant ignition risks during operation and servicing of RTUs using R-32 (GWP of 675) and R-1234yf (GWP of 4). The study consisted of CFD modeling of the refrigerants dispersion patterns for different leak scenarios and a fault tree analysis to evaluate the likelihood of refrigerant ignition. This section is a high level summary of the research work done by Navigant Consulting under a project funded by AHRI. More detailed information is contained in the project final report [13].

3.1. Equipment and risk scenarios

The equipment investigated in the study was packaged RTUs. These units could be either installed on the roof or the ground. Three different application/installation scenarios were evaluated in this study including rooftop mount and ground mount, described in Table 5.

Table 5. Risk scenarios (Table source: AHRI Project 8016 Report [13])

Scenario	Refrigerant	Equipment	Building	Description
A	R-32	15-ton on Roof	Kitchen	Two-circuit unit (5 ton and 10 ton capacities) mounted on the roof directly above the conditioned space, which consists of just the kitchen space (no dining areas).
B	R-1234yf			
C	R-32	25-ton on Roof	Office	Two-circuit unit (12.5 ton capacity each) mounted on the roof directly above the conditioned space; return and supply ducts serve multiple office spaces.
D	R-1234yf			
E	R-32	5-ton on Ground	Office	Single-circuit RTU that is mounted on the ground adjacent to the conditioned space; multiple return ducting configurations are considered, including directly ducted horizontally, and ducted vertically up into the roof of the building.
F	R-1234yf			

For the ground-mounted RTU analyzed in Scenarios E and F, two different return venting configurations were modeled. The first had a horizontal return duct that passed directly from the ground-mounted RTU to the office through a grill in the office wall, and the second had a vertical return duct that rose up the outside wall and entered the office through the ceiling, similar to the supply duct. Both of these configurations were included in the FTA for Scenarios E and F. Operating states included normal operation and installation and servicing [13].

3.2. Modeling of refrigerant dispersion

The refrigerants dispersion patterns were investigated by using a proprietary Computational Fluid Dynamics (CFD) tool. A number of cases were simulated in this study. The refrigerants' quantities, leak type, and leak locations are summarized in Table 6 below. The simulation covered various scenarios consisting of fast leak, slow leak with blowers on or off. It was assumed that R-32 and R-1234yf systems had different charge level in the simulation to reflect realistic conditions because charge levels of actual systems will depend on system design. For comparable efficiency, capacity and heat exchange technology, a low pressure refrigerant will likely have a higher charge level than a high pressure refrigerant because of lower density.

In the simulation, it was assumed that the vapor phase refrigerant was leaked with equalized pressure inside the refrigerant circuit. A decaying leak rate was modeled to simulate the change of pressure difference between the outside ambient and inside the refrigerant circuit while a leak occurs. The decaying leak rate was validated in leak-chamber testing for ASHRAE project 1580 [14].

Figure 2 is an example of CFD results. It illustrates the refrigerant dispersion when the leak occurs inside the rooftop unit on top of a commercial kitchen and dispersed into the kitchen through the return duct. Figure 2a shows a screenshot of flammable concentrations developed from a fast evaporator leak of R-1234yf from a 15 Ton RTU on a commercial kitchen at 52 s after the leak began. All regions between the Lower Flammability Limit (LFL) and the Upper Flammability Limit (UFL) are colored by concentration. Figure 2b shows concentration changes over time at various monitored points inside the kitchen and rooftop unit [13].

The CFD simulation demonstrated likely flammable cloud formation in each of three primary locations: inside the RTU and ventilation system, outside the RTU (and outside the building), and inside the conditioned space [7]. Table 7 summarizes at a high level the flammable concentration buildup for each location in each CFD scenario.

Table 6. CFD matrix (Table source: AHRI Project 8016 Report [13])

No.	Equipment Type	Refrigerant	Charge in leaked circuit (lb)	Leak Type	Leak Location /Condition	Leaked circuit size (Tons)	Notes
1	15T on rooftop	R-32	12	Fast	Evaporator/Blower off	10	Exhaust hoods off
2	15T on rooftop	R-1234yf	17	Fast	Evaporator/Blower off	10	Exhaust hoods off
3	15T on rooftop	R-32	12	Fast	Evaporator/Blower on	10	Exhaust hoods off, assumed min. blower speed
4	25T on rooftop	R-32	23	Slow	Evaporator/Blower off	12.5	
5	25T on rooftop	R-32	23	Fast	Evaporator/Blower off	12.5	
6	25T on rooftop	R-32	23	Fast	Condenser/Condenser Fan Off	12.5	Assumed low wind speed (1 m/s)
7	5T on ground	R-32	7	Fast	Evaporator/Blower off	5	Supply & return ducts run vertically to roof
8	5T on ground	R-32	7	Fast	Evaporator/Blower off	5	Same as #7 , but with horizontal return air ducting
9	5T on ground	R-1234yf	10	Fast	Evaporator/Blower off	5	Same as #8 with different refrigerant
10	15T on rooftop	R-1234yf	17	Fast	Evaporator/Blower on	10	Same as #3 with different refrigerant

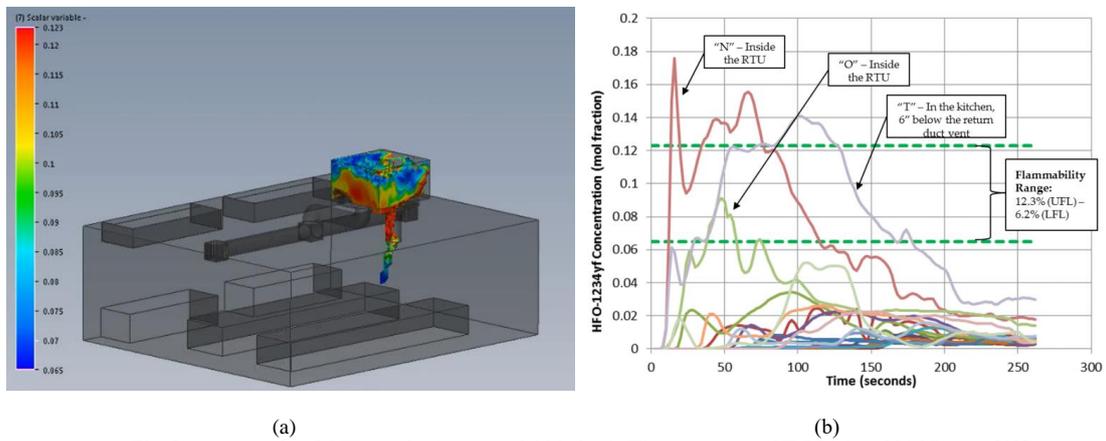


Fig. 2. An example of CFD results (commercial kitchen) (Figure source: AHRI Project 8016 Report [13])

Table 7. Summary of CFD analysis results (Table source: AHRI Project 8016 Report [13])

#	Did a substantial plume accumulate with a flammable concentration?		
	Inside the RTU/Ventilation	In Conditioned Space	Outside the RTU
1	●	●	○
2	●	●	○
3	●	○	○
4	●	○	○

#	Did a substantial plume accumulate with a flammable concentration?		
	Inside the RTU/Ventilation	In Conditioned Space	Outside the RTU
5	●	●	○
6	●	○	●
7	●	○	○
8	●	●	○
9	●	●	○
10	●	○	○

Legend:
 ● - Substantial Flammable Plume ● - Small Flammable Plume ○ - No Flammable Plume

3.3. Fault Tree Analysis (FTA)

FTA was used to quantify the potential refrigerant ignition risks. The FTA analyzes the potential combinations of events that might lead to refrigerant ignition, and provides an order of magnitude estimate of the likelihood that refrigerant ignition will occur. One should note that the FTA in this study only evaluated the likelihood of refrigerant ignition and did not determine whether the ignition will actually result in a fire due to the ignition of surrounding materials. The total predicted ignition risk was based on several probabilities, including the likelihood of: (1) a refrigerant leak, development of flammable concentrations of leaked refrigerant, presence of an active ignition source, and (2) a local velocity that does not exceed a threshold above which refrigerant ignition is not possible [13].

An important consideration in all of the fault trees is the requirement that ignition sources strong enough to ignite the refrigerant have to be present at the same time and location as the flammable concentration of refrigerant, and the local air velocity does not exceed 2.5 times of refrigerant’s burning velocity [13]. If the refrigerant does not exceed the LFL throughout the space, the presence of an ignition source in a part of the room where the LFL is not exceeded creates no risk. Similarly, if the time a flammable concentration occurs does not coincide with the time an ignition source is present (i.e., a gas heater is switched on, a wiring short occurs) or the refrigerant local velocity exceeds the threshold then there is also no risk.

Fault trees were constructed using a commercialized software tool. An example of fault tree with input probabilities included is shown in Figure 3.

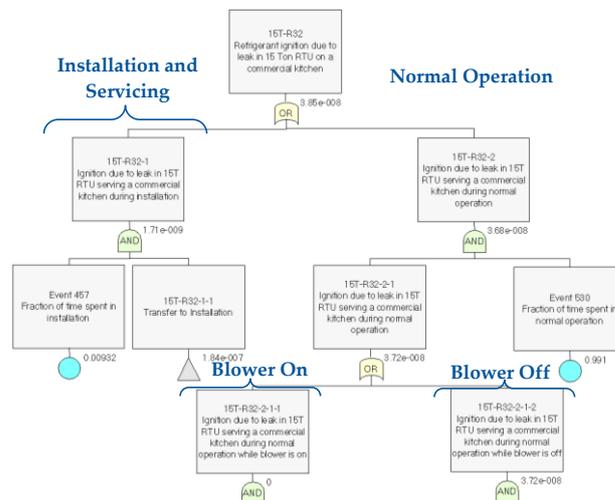


Fig. 3: Fault tree example (Figure source: AHRI Project 8016 Report [13])

The overall fault tree consists of the two primary branches: normal operation and installation and servicing. Each contains five primary variables that drive the ignition risk [13]:

- Refrigerant leak (either fast or slow)
- Flammable concentration develops in same location as ignition source as a result of the refrigerant leak (informed by CFD analysis)

- Presence of active ignition source during period of flammable refrigerant buildup
- Ignition source is active with energy greater than the refrigerant minimum ignition energy (MIE)
- Flammable concentrations are not in a region with local velocity greater than 2.5x the refrigerant burning velocity

In the FTA, five different ignition sources below were considered for various scenarios and summarized in Table 8

- Hot surface – malfunctioning heating element in an RTU or space heater
- Electrical spark – could occur from failed motor, faulty appliance, spark igniter, wiring short, or high voltage contactor
- Brazing torch – could be used during installation or servicing
- Cigarette lighter
- Gas-fired equipment – including cooking and water heating equipment

Table 8. Analyzed ignition sources by location and operating mode (Table source: AHRI Project 8016 Report [13])

Location	Ignition Source	Kitchen (Scenarios A, B)		Office – on rooftop (Scenarios C, D)		Office – on ground (Scenarios E, F)	
		Normal Operation	Installation and Servicing	Normal Operation	Installation and Servicing	Normal Operation	Installation and Servicing
Outside RTU	Cigarette lighter	✓	✓	✓	✓	✓	✓
	Brazing torch		✓		✓		✓
Inside RTU	Spark	✓	✓	✓	✓	✓	✓
	Brazing torch		✓		✓		✓
In Conditioned Space	Pilot (cooking equipment)	✓	✓				
	Spark	✓	✓	✓	✓	✓*	✓*
	Cigarette lighter	✓	✓	✓	✓		

* In the scenarios with a ground-mounted RTU serving an office, ignition within the conditioned space was only analyzed for RTUs with a horizontal return ducting configuration, because CFD results from Scenarios 7 and 8 show that flammable concentrations only develop in the office with this ducting configuration.

The FTA results are summarized in Table 9. For all the scenarios, the largest ignition risk is associated with rooftop unit for commercial kitchen application. Risks of this event were on the order of 3.9×10^{-8} events per unit per year for R-32 (~1 ignition per 25 million units per year) and 8.5×10^{-9} events per unit per year for R-1234yf [13].

The risks of refrigerant ignition from this study were compared to risks related to other events derived from data reported in government or scientific publications. These comparison risks are shown in Table 10. Table 10 demonstrated that the risks due to refrigerant release and ignition (almost entirely attributable to a leak in the outdoor condensing unit) are far below risks of other hazards that are commonly accepted by the public [13].

Table 9. Fault tree analysis results by scenario in descending order of risk (Table source: AHRI Project 8016 Report [13])

Scenario	Refrigerant	Equipment	Location	Annual Risk of Ignition*
A	R-32	15T on Roof	Kitchen	3.9 E-8
B	R-1234yf	15T on Roof	Kitchen	8.5 E-9
C	R-32	25T on Roof	Office	8.0 E-11
D	R-1234yf	25T on Roof	Office	3.0 E-11**
E	R-32	5T on Ground	Office	1.8 E-11
F	R-1234yf	5T on Ground	Office	7.0 E-12**

*Units for risk are occurrences (refrigerant ignitions) per scenario per year
 **Results for Scenarios D and F were obtained by scaling results from Scenarios C and E, based on the relative risks for ignition of R-32 and R-1234yf observed from Scenarios A and B.

Table 10. Safety hazard risk (annual frequency) levels for various activities (Table source: AHRI Project 8016 Report [13])

	Safety Hazard Risk	Risk (unit/year)
	Fatal injury risk for worker in the mining, quarrying, and oil and gas extraction industry	1.2 E-4
	Occupant fatality risk in traffic crash (per person in U.S.)	8.5 E-5
	Fatal injury risk on the job for employed people in the U.S.	3.3 E-5
	Non-occupant fatality risk in traffic crash (per person in U.S.)	1.8 E-5
	Injury risk for park attendee on amusement park ride	4.7 E-6
Higher→	Frequency of ignition in residential heat pump using R-32	3.7 E-6
	Frequency of ignition in 100T chiller with unrestricted airflow using R-32	8.3 E-7
	Annual refrigerant ignition risk in scenario A	3.9 E-8
	Annual refrigerant ignition risk in scenario B	8.5 E-9
	Annual refrigerant ignition risk in scenario C	8.0 E-11
	Annual refrigerant ignition risk in scenario D	3.0 E-11
	Annual refrigerant ignition risk in scenario E	1.8 E-11
	Annual refrigerant ignition risk in scenario F	7.0 E-12

4. Summary

AHRI research activities on heat pumps evaluated several low-GWP alternative refrigerants, all mildly flammable. Many alternative candidates demonstrated comparable performance than the baseline refrigerant R-410A. These results were obtained from drop-in and soft-optimized tests performed on equipment designed for the baseline refrigerants, therefore further performance improvement of these alternatives is possible through full optimization. However, this was beyond the scope of the Low-GWP AREP. The test results should be carefully interpreted along with system modifications, test procedure variations etc. [2].

Additional research looked at the risk assessment of using mildly flammable refrigerants in packaged RTUs for commercial kitchens and office buildings. The potential ignition risks of R-32 and HFO-1234yf in RTUs during operation and servicing were investigated. The risk assessment demonstrated that the ignition risks of the A2L refrigerants in RTUs are significantly lower than common hazard events [13]. The current analysis did not include potential mitigation (e.g., system design changes) that would further reduce the probability of refrigerant ignition.

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