

Flammable Refrigerant Charge Limits: Can or Should These Limits Be Higher?¹

ABSTRACT

A workshop was held to discuss different aspects of the application of flammable refrigerants in refrigeration and air conditioning equipment. The participants included stakeholders from industry, regulatory bodies, and the scientific community. The goal was to solicit feedback on the critical scientific, regulatory and practical issues for safe employment of flammable refrigerants in heating, ventilation, air-conditioning and refrigeration equipment. This paper reports on the outcome of the workshop and presents review of relevant past studies when available. The reported outcome may serve well as a guide to further research needed as adoption of flammable refrigerants increases.

1 INTRODUCTION

Environmental protection goals are becoming progressively stricter to reduce negative global environmental impacts of refrigerants. Hydrofluorocarbons (HFCs) like R410A and R134a are used for many HVAC&R applications but have relatively high global warming potentials (GWP). In October 2016, the Kigali Amendment to the Montréal Protocol was adopted to phase-down the use of HFCs in developed countries to be reduced to 15% of the average consumption for 2011-2013 by 2036 [1]. Proposed lower GWP alternatives to HFCs fall in several categories: hydrocarbons (R290), inorganics (R717, R744), hydrofluoroolefins (HFO) or blends of low-GWP HFCs and HFOs. Many of these alternatives are flammable, listed as A2L, B2L, A2, or A3 in ASHRAE 34 [2]. This presents new challenges to the usage of these refrigerants centered around the personal safety and the deflagration risks associated with using flammable material. Safety standards include charge limits for flammable refrigerants to ensure safety in case of leakage. These limits were based on numerical analyses of refrigerant leakage into confined spaces as well as risk analyses of associated ignition events. Despite the large number of studies that investigated the usage of flammable refrigerant, there remains research gaps that need to be covered as basis for the development of the relevant standards. In 2016, the Air Conditioning, Heating and Refrigeration Institute (AHRI), the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), the California Energy Commission (CEC) and the United States Department of Energy (DOE) undertook a collaboration to advance research to facilitate wider use of flammable refrigerants.

Oak Ridge National Laboratory (ORNL) initiated a project under this collaboration to examine the current limits and identify reasonable adjustments as appropriate. On October 24, 2016 ORNL held a workshop to

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solicit input from stakeholders to help guide the project. Attendance at the workshop was by invitation only. Invitees were selected based on consultation with members of the AHRTI Flammable Refrigerants Subcommittee and the Association of Home Appliance Manufacturers (AHAM.)

ASHRAE hosted the workshop in Atlanta. Forty invited stakeholders participated in the workshop, joining seven ORNL and DOE staff. These included experts from HVAC&R and appliance original equipment manufacturers (OEMs), refrigerant manufacturers, standards/codes development organizations, industry and professional organizations, and representatives from the United States Environmental Protection Agency (EPA).

The workshop objective was two-fold: 1) engage the stakeholders in discussions to elicit input regarding gaps in R&D related to safe application of flammable refrigerants, safety standard information/updates needed, critical factors to include in computational fluid dynamics (CFD) analyses phases of the project, and primary practical issues to consider in the analyses; and 2) identify a few primary case studies or scenarios for investigation.

2 WORKSHOP PROCESS

The workshop program began with a discussion of current and planned revisions relevant to safety standards particularly Annex GG of the International Electrotechnical Commission standard IEC 60335-2-40 [3], discussion of previous work related to flammable refrigerant charge size evaluation and current R&D efforts, and the intended analysis approach. Four breakout sessions followed for detailed discussion of relevant topics. Ideas and suggestions generated during the breakouts were assigned priorities via vote by the participants. After the breakouts, a final session was held to discuss and prioritize the most relevant case studies to be pursued for further analysis.

3 WORKSHOP RESULTS

The breakout sessions generated a total of 71 unique topics for consideration in the project analyses and/or future efforts. During the final session, 4 unique case study priorities were identified. The following tables document the highest voted ideas proposed along with the number of votes each one received. The tables are followed by discussion of the top priority initiatives from each breakout.

Table 1. Ideas and suggestions from breakout session 1a (What are the relevant R&D gaps?)

Idea/suggestion	Votes
Severity of refrigerant combustion event	17
Characterization and probability of leaks	16

Minimum leak rate of worst-case scenario for each type of equipment	14
Available ignition energy of common electric components	11
Necessity of validating of CFD results	11

Table 2. Ideas and suggestions from breakout session 1b (Do we have enough information in the safety standard?)

Idea/suggestion	Votes
Certification requirements of technicians	18
Developing training modules and standards for servicing flammable refrigerants equipment	17
UL, ASHRAE and AHRI standards timeline vs building code timeline	11
Split system exclusion from hydrocarbon use	10

Table 3. Ideas and Suggestions from breakout session 2a (What are the most important factors to consider in the CFD analyses phase of the project?)

Idea/suggestion	Votes
Release locations	12
Boundary conditions	12
Variable vs. constant leak rate	10
Liquid vs. vapor leak	9

Table 4. Ideas and Suggestions from breakout session 2b (What are the practical issues that we need to study?)

Idea/suggestion	Votes
Leak rate assumptions	13
Effectiveness of detection and circulation (ducted and ductless)	11
Utility closet	10

3.1 Severity of refrigerant combustion event

Currently, the criterion of safe installation is based solely on the maximum predicted concentration of refrigerant in air in case of a leak. The rationale is that if the maximum concentration does not exceed the lower flammability limit (LFL), the refrigerant-air mixture will not ignite. However, in a leak event, there will inevitably be locations where the local concentration exceeds LFL. The mass of refrigerant present within the combustibility limits and how long this mass persists directly affects the probability of an ignition event. If this flammable mass ignites, several factors affect the severity of the event. Heat release and the rate of heat release are indications of the magnitude of the resulting potential damage. In addition to providing a prediction of whether maximum refrigerant concentration will exceed LFL, leakage models should also provide an estimate of how much flammable mass is present and its presence time. Modeling efforts should also consider deflagration models to characterize the heat release, the rate of heat release and the pressure rise that will result from an ignition event. ASHRAE project 1806-TRP is aimed at understanding the severity of events where flammable refrigerants are ignited under different scenarios for various HVAC&R products². Combustion of flammable refrigerant upon a leakage event has been investigated in a few studies (c.f., Zhang, et al. [4] and Jabbour and Clodic [5]) but remains largely under-characterized. The severity of a possible ignition event may be a suitable criterion but “severity” itself should be defined consistently whether it is pressure rise, amount of smoke, heat release or any other relevant quantity or combination of relevant quantities.

3.2 Characterization and probability of leaks

The location, size, and orientation of a refrigerant leak will affect its spatial dispersion pattern. One or more of these variables could be the deciding factor of whether the leak results in an unsafe event or not. Statistical data on the frequency of occurrence of leaks is scarce. Sometimes this data must be synthesized from different sources or assumptions need to be made. This data is critical input to risk assessment models, therefore, reliable statistical field data on refrigerant leaks needs to be compiled to provide inputs that are truly representative of real life scenarios. Past studies have used different sources for refrigerant leak frequency data. Goetzler, et al. [6], Goetzler, et al. [7] and Lewandowski [8] used proprietary data supplied by three major heat pump manufacturers. A survey tool needs to be built to collect this data from service contractors and manufacturers.

3.3 Minimum leak rate of worst-case-scenario for each type of equipment

The size of a leak source, pressure and temperature of the refrigerant determine the rate of discharge of the refrigerant from the equipment into its surrounding space. Leak sources vary in size from the most common pinholes and cracks to the less common larger line or component ruptures. Ruptures are less likely to occur but result in much more severe consequences. Pressure and temperature of the refrigerant charge determine

² At the time of writing this paper, the project research report had not been published yet.

the phase of the leaking refrigerant; liquid, vapor, or two-phase. This affects the rate of discharge of the refrigerant from the leakage source. Different refrigerant dispersion studies have used different leak rates. In some instances, leak rates were modeled based on assumed leakage source size and operating conditions. Colbourne and Liu [9] developed a physics-based model to predict the leakage flow rate of R290 following an instantaneous occurrence of a leak for a system in off-mode. In other instances, leak rate was chosen and assumed to remain constant. Kataoka, et al. [10] chose the leak rate based on a 4-minute leakage time which was adopted in the IEC-60335-2-40. There is no universally accepted model or estimation procedure for leak rates for different equipment types at different operating conditions. Reliable data/information about minimum leak rates due to catastrophic failures of each type of equipment is needed to reliably assess the associated risks.

3.4 Available ignition energy of different common electric components

Sparks from electric components of HVAC&R systems or appliances could be ignition sources. For example, it is not uncommon for sparks to occur when an appliance is plugged into a wall outlet. Other examples of electric components that may produce sparks include switches, relays, and loose wires. Recent AHRI Project [11] identified 15 ignition sources in residential applications. The viability of each of these sources igniting R1234yf or R1234ze was experimentally tested. similar studies are needed for commercial and industrial applications.

3.5 Necessity of validating of CFD results

Most risk assessment models rely on CFD simulation of a refrigerant leakage into a confined space to quantify the presence, the location, and sometimes the presence time of flammable volume. CFD is a powerful tool to characterize dispersion of gases into a space. However, CFD results are directly influenced by the setup of the model; variables such as what turbulence model is employed and the specified boundary conditions. Other factors are even harder to accurately account for such as initial air motion inside the space and infiltration. CFD models employed in risk assessment models must be calibrated experimentally to ensure validity of the results. Validation not only verifies the accuracy of the results, but also provides insight to what CFD model set up yields best results.

3.6 Certification requirements of technicians

Risk of ignition is greater during equipment servicing than during normal operation. This is due to inclusion of the additional risk factor of probability of human error. Currently in the US, Section 608 of the Clean Air Act mandates the certification of technicians who service HVAC units with refrigerants having non-zero ODP, but not for flammable refrigerants. Certification requirements need to be revised to ensure that technicians who work on equipment that employ flammable refrigerants are aware of the associated risks.

3.7 Develop training modules and standards for servicing flammable refrigerants

equipment

The increased risk of ignition during servicing results from the introduction of risk associated with human error and abundance of sources of ignition. Wrong use of tools, disregarding warning signs and not replacing safeguards are few examples. Best practices for servicing flammable refrigerant equipment need to be developed. Recently, the American Association of Home Appliance Manufacturers (AHAM) developed guidance for safe servicing of appliances with flammable refrigerants Manufacturers [12] that could be a basis to develop training modules. There is also a flammable refrigerant technician training program that was developed by the Refrigeration Service Engineers Society (RSES) that can provide a basis for developing updated training modules. The ASHRAE research project 1807-RP³ will also provide valuable input to any training development process. With several programs currently under development, it may be better if they unified their approach.

3.8 UL, ASHRAE and AHRI standards timeline vs. Uniform Building Code timeline

Several standards that are relevant to the use of flammable refrigerants in HVAC equipment are presently under revision. The most relevant ones are UL 60335-2 -24 [13] and -40 [14], IEC 60335-2 -24 [15] and -40 [3], ASHRAE 15 and the International Building Code (IBC) [16]. The most recent UL 60335-2-24 and UL 60335-2-40 were published in 2017. The updated IEC 60335-2-24 and IEC 60335-2-40 are scheduled to be published in early 2018. The next edition of ASHRAE Standard 15 is due to be finalized in January 2018. The International Building Code (IBC) has a three-year development cycle, the most immediate of which starts in 2018. This means that the revised IEC, ASHRAE, and UL standards will not be adopted in the IBC until 2021 at earliest. This is problematic for the industry since the phase out schedule of HCFC-22 enforces no production or import in 2020.

3.9 Split system exclusion from hydrocarbons

Split systems require on-site welding and usually the connecting lines between indoor and outdoor sections have many joint, increasing the probability of refrigerant leakage during installation. Split system-focused analysis should be done to investigate if the risks with split systems are manageable. Until then, some attendees suggested that flammable refrigerants should be excluded from use in split systems.

3.10 Release location

Leak location has a major effect on the refrigerant dispersion pattern. Release height is a well-investigated parameter in both numerical and experimental flammable refrigerant dispersion studies. On the other hand, the effect of leak orientation on the dispersion is under-investigated. Most, if not all, studies assume a downward leakage since it was considered the most conservative scenario based on results presented in

³ The final report had not been published at the time of writing this paper.

Kataoka, Yoshizawa and Hirakawa [10]. More investigative work should be conducted to validate the universality of this assumption.

3.11 Boundary Conditions:

Boundary conditions are important in determining the evolution of leaked refrigerant distribution. Walls and furniture are examples of boundaries that redirect the flow. Room air velocity field and ambient temperature are other examples of boundary conditions that affect the dispersion pattern of the leaked refrigerant. However, most studies have assumed quiescent room air and empty space. Boundary conditions should be accurately considered in the CFD simulations of refrigerant leakage scenarios.

3.12 Variable or constant leak rate:

In real life scenarios, the discharge rate of leaked refrigerant decays with time as pressure inside the system depletes. The size of the leakage source, pressure and temperature of the refrigerant in the system and the amount of charge affect the pressure decay rate, and hence, the flow rate of the leaking refrigerant. Most prior studies have assumed constant leak rate to represent the worst-case scenario. A new joint AHRTI-ORNL project (AHRTI 9012), was initiated in late 2017, with the objective to characterize leaks from different equipment under different operating conditions. This project is expected to be completed in late 2018.

3.13 Leak rate assumption

Refrigerant leak rate depends on the dimension and overall shape of the leakage source, pressure and temperature of the refrigerant in the system, and the mass of refrigerant charge. The latter two factors continuously change until leakage stops. Different studies assumed different leak rates. Some determine leak rates based on a fixed leak time of four minutes (based on the time required for 150g of CO₂, which has similar molecular weight to R290, to leak through a capillary tube as defined in IEC-60335-2-24). Other studies have measured leak rates; some closely matching the 4-minute assumption and some not. Since the rate of leaking refrigerant release directly affects the dispersion of the refrigerant, leak rate assumptions need to be representative of realistic leakage scenarios.

3.14 Effectiveness of detection and circulation:

The location of refrigerant leak detection sensors and leak circulation patterns are sensitive to the leak nature, location and boundary conditions. Generally, in any leakage event, if the measurement point is moved close enough to the leakage source, the concentration will inevitably exceed LFL. Determination of optimal leak detection locations is dependent on an accurate estimation of the gas dispersion scenario. The analyses need to provide information for refrigerant sensor locations to best ensure reliable early indication of refrigerant leakage events.

3.15 Utility Closet:

Equipment location inside utility closets is agreed to be a worst-case scenario due to the typically low ventilation rate and the confined nature of such closets. It is expected that refrigerant concentration in such a space would exceed LFL rather quickly. Special attention should be paid to the utility closet scenario when developing charge limits.

3.16 Case Studies

The top priority CFD case studies identified are presented below in votes-ascending order.

3.16.1 Case 1: Residential split heat pump air handler unit in utility closet (2 Votes)

This would be a parametric study of the effect of leak rate, velocity, location and size of leak hole on the maximum refrigerant concentration inside the closet. The study should also consider different mitigation strategies and identify effective ones. Seasonal effects on the intra unit charge residence (air handler versus outdoor unit) should also be considered. Different leak scenarios to be modeled were suggested: leakage with the presence of a furnace (hot surface), leakage with the presence of water heater with a standing flame, leakage inside versus outside the air handler. This case will only be included in the scope of the current ORNL project if time/resources permit.

3.16.2 Case 2: m1, m2 and m3 (5 Votes)

The current relevant standards define three incremental charge limits (m1, m2, or m3) based on the room volume and the lower flammability limit (LFL) of the refrigerant in question. They then define requirements based on where the actual charge falls in relation to these incremental limits. The premise is that if requirements are followed, the maximum concentration of refrigerant the room will not exceed LFL in case of refrigerant leakage. Models of scenarios that meet the requirements of the relevant standard need to be developed to validate or invalidate the underlying premise of the standard.

3.16.3 Case 3: Leak profiles in various applications of RTU, mini split and VRF units (10 Votes)

This would be a CFD campaign to identify the spatial concentration profiles for different leakage scenarios: point source vs. distributed source, high vs. low velocity, high mass vs. low mass, liquid vs. two-phase vs. vapor, rupture of compressor (high electrical discharge), constant vs. variable leak rate, existence of mitigation vs not.

3.16.4 Case 4: Room that meets minimum floor area requirements for m2 (13 Votes)

Reasonable obstructions would be added to the modeled space to represent a more realistic space. Leakage of mass charge equal to m_2 would be modeled at different leak rates and with different refrigerants. Results

would be analyzed to investigate if a function could be created that describes the concentration as a function of refrigerant, charge mass and leak rate.

4 CONCLUSION

Given the current emphasis on minimizing usage of high-GWP refrigerants in HVAC&R equipment and other appliances, increased use of lower-GWP alternatives, most of which are flammable to some degree, appears quite likely. Standards regulating flammable refrigerant charge limits have existed for a relatively long time. Work needs to be done to ensure that charge guidelines are based on scientific basis that accounts for imperfections and variability of real life applications. Reasonable safe charge limits are only one criteria among many that must be determined to facilitate safe use of flammable refrigerants. Training modules for service workers and certification requirements are critical to reduce the human error risk factor. Regulations for labeling, transportation and storage need to be developed specifically for equipment that use flammable refrigerant. This requires coordination among all stakeholders across the value chain. Professional societies and national laboratories facilitate this coordination.

Finally, the outcomes of the workshop reflect the perspectives of scientific community, equipment manufacturers and regulating bodies. The outcomes presented in this paper may serve well as a guide for further investigation and future projects that aim at increasing adoption of flammable refrigerants in HVAC&R equipment.

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