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Evaluation of the Fire Hazard of ASHRAE Class A3 Refrigerants in Commercial Refrigeration Applications

FINAL REPORT BY:

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FOREWORD

Due to the potential environmental impact, there has been a shift to consider use of natural refrigerants, which have a lower Global Warming Potential (GWP) than traditional fluorocarbon-based refrigerants. One type of natural refrigerant are hydrocarbons (e.g. propane), which are classified as Class A3 refrigerants per ASHRAE Standard 34. The Environmental Protection Agency (EPA) has a charge limit of 150g of hydrocarbon per appliance, which is defined as a closed loop refrigeration circuit. Previous work has been completed on Class A2L refrigerants, but Class A3 refrigerants need more study to provide technical basis for any changes to the current limits for use in refrigerator units. There is a need to assess the fire hazard of Class A3 refrigerants, and specifically propane, in larger volumes to evaluate their viability as alternatives to traditional refrigerants in more applications.

The Fire Protection Research Foundation expresses gratitude to the report author Dr. Scott G. Davis and the research team at Gexcon, whose US headquarters is located at 4833 Rugby Avenue, Suite 100, Bethesda, MD 20814. The Research Foundation appreciates the guidance provided by the Project Technical Panelists, the funding provided by the project sponsors, and all others that contributed to this research effort.

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Keywords: R-290, propane, refrigerant flammability, ASHRAE class A3, risk assessment, ignition consequences of A3 refrigerants, charge size, LFL, UFL, accidental releases.

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October 16, 2017

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Executive Summary

This study evaluated the flammability hazard of R-290 propane in refrigeration appliances used in commercial retail and kitchen settings. The specific objectives were to: (1) assess the flammability risk versus charge size; and (2) develop recommendations on how to prevent or mitigate the risks when using R-290 in commercial retail and kitchen applications. This type of study is needed to establish a technical basis for any changes to the current charge limits and to help determine whether A3 refrigerants can replace non-flammable refrigerants in a broader range of refrigeration applications that require larger charges than currently allowed by standards.

When a flammable refrigerant is released from a refrigeration cycle, there are several factors that affect the potential severity of the event including properties of the refrigerant, characteristics of the leak, properties of the equipment, and aspects of the environment. Two very important factors that must be considered are: (1) the increased release rates associated with leaks in the liquid lines and (2) whether releases in confined areas, like the condensing unit housing, impinge on adjacent surfaces and lose their momentum. The present study considered these two main factors, along with many others, and used computational fluid dynamics (CFD) to examine in detail how each factor influenced the outcome of a leak.

Full-scale testing quantified the severity of various refrigerant releases and associated post-ignition events for different charge sizes. Coupling the experimental results with CFD simulations revealed that severity (in terms of thermal exposure and overpressure) was related to the mass of R-290 that participated in the combustion event once ignited. While this variable was limited by the charge size, it was also strongly dependent on how well R-290 mixed with air in the room during the release. This was because better mixing with air resulted in more dilution of R-290 below the lower flammability limit and therefore less R-290 participating in the combustion event once ignited.

A quantitative assessment of relative risk versus charge size was performed using inputs from the full-scale experiments, CFD dispersion simulations, and an analysis of the likelihood of various outcomes. The assumptions of this study were intended to establish an upper bound for the absolute risk. As such, conservative assumptions were employed in the present study to maximize accumulated fuel volumes and ignition consequences. Considering the conservatism in the approach and the inherent uncertainty associated with the leak frequencies, it is more appropriate to discuss relative risk in the present analysis. The focus of the assessment was to examine larger charge sizes and possible mitigation effects that could be implemented as part of the design and installation of refrigeration units. The approach of using relative risk facilitates investigation of these effects with reduced sensitivity to some sources of uncertainty, e.g. leak frequencies. Summarized below are the main findings:

- As charge size increases, the probability of an ignition event increases as the mass of R-290 available to accumulate within the space also increases.
- Servicing generally represents a small contribution to the overall frequency of an ignition event assuming that the refrigerant is either recovered or vented prior to servicing and that proper procedures are followed.

- The frequency of an ignition event is 1.2-2.0 times lower when condensing units are top-mounted compared to bottom-mounted as external leaks from top-mounted units tend to mix more with air in the space where the equipment is located.
- While there is only a marginal benefit to running the condensing unit fan all the time when the condensing unit is top-mounted, it is more beneficial when the condensing unit is bottom-mounted. For example, the ignited event frequency is generally up to 3.2 times lower for the fans 100% on compared to 60% on for bottom-mounted units.
- The likelihood of an ignition event is similar for bottom-mounted and top-mounted units when the condensing unit fan is operated continuously.
- In-cabinet releases represent a large portion of the risk for closed display cases in large rooms. For example, in the big-box store geometry, internal leaks contribute 75% of the total ignited event frequency.

Based on the findings from this study, the following are recommended:

- Charge size should be limited based on room volume as similarly done in EN 378 (e.g., charge size should be limited to 20-25% LFL when homogeneously mixed in the room volume). The exact recommended charge limit should be determined from more refined CFD and experimental data and once acceptable risk tolerance criteria have been established.
- Under normal operation (e.g., condenser fan in operation 60% of the time), top-mounted condenser designs result in reduced risk of ignition events compared to bottom-mounted designs.
- Always have the condenser fan running, or at a minimum activated upon leak detection from sensors installed on the equipment.
- Requirements regarding room ventilation or automatic activation upon confirmed leak detection, should be investigated as a potential means of mitigating unintentional refrigerant releases.
- All equipment within a closed refrigerator cabinet shall be designed and rated for use in explosive atmospheres (e.g., explosion proof or Ex rated).
- Additional studies are needed to evaluate the "actual" infiltration into closed refrigerator cabinets in order to better quantify the risk. As in-cabinet releases are not affected by fan operation, additional effort should go into appropriate mitigation strategies, such as passive or active ventilation within the cabinet.

The quantitative assessment evaluated the likelihood of fire events and compared the frequencies of various scenarios to a particular scenario (a bottom mounted 150 g (0.33 lb) unit in a small kitchen) that would be permissible with current regulations in order to establish conclusions on the use of various charge sizes. This relative risk assessment is a means to better understand the implications of larger charge sizes despite the absence of selected risk acceptance criteria and uncertainty regarding leak frequency data. The table below summarizes the results. A check mark indicates that the frequency of a fire is the less than that of the base scenario. An 'x' indicates that the likelihood of a fire is greater than that of the base scenario. The data in this table is based on the models and assumptions described in this report and should not be assumed to universally apply in all situations.

Charge Size and Geometry Scenarios						
Area (m^2)	11	13	28	33	56	256*
Area (ft^2)	405	441	1000	1159	1978	9040*
Charge Size	**Sm. Store**	**Sm. Kitchen**	**Deli**	**Market**	**Med. Kitchen**	**Big Box Grocery**
150g	✓	✓	✓	✓	✓	✓
300g	×	×	✓	✓	✓	✓
450g	×	×	✓	✓	×	✓
600g	×	×	×	✓	×	✓
1000g	×	×	×	×	×	✓

* The Big Box Grocery area is for the relevant region of the store where refrigerated display cases are located and does not include the entire store.

The results could be refined and updated based on the selection of a particular risk acceptance criteria (i.e. a combination of consequence and frequency that would be tolerable). There is fine granularity in the risk model to examine the frequency of an event with a particular consequence in terms of the potential harm to people or property.

In order to refine the work and recommendations in the present study for the safe operation of R-290, future work should include enhancing various aspects of the risk assessment including:

- Accounting for actual mechanical ventilation in the room where the release occurs
- Evaluating actual air infiltration into closed refrigerator cabinets and refine how in-cabinet releases are represented
- Accounting for evaporative cooling and depressurization on the transient nature of the leaks in actual refrigeration systems while in operation and idle (liquid and vapor)
- Including a time-dependent ignition model
- Evaluating additional detection and mitigation options, such as room ventilation, condenser fans, and cabinet ventilation
- Obtaining additional information on actual equipment leak frequencies
- Additional studies to understand risk of venting HCs outside versus reclaiming
- Understanding the relationship between proximity to ignition sources and likelihood of ignition, especially in kitchens, and leveraging this understanding to make recommendations on equipment location restrictions that may further reduce risk.

1 Introduction

1.1 Background

Hydrocarbons, including R-290 (propane), are viable refrigerant working fluids with zero ozone depleting potential (ODP) and minimal global warming potential (GWP). The current barrier to more widespread application of hydrocarbons as refrigerants, and A3 refrigerants in general, is their flammability. While fundamental flammability characteristics are well established for most hydrocarbons, there is a need to assess the risks associated with their use as refrigerants and evaluate methods to mitigate such risks, specifically when charge sizes are larger than the currently mandated limits. Further studies are needed to establish a technical basis for any changes to the current charge limits in refrigeration appliances. Furthermore, assessing the risk for larger charge sizes than currently allowed by standards will help determine whether A3 refrigerants can replace hydrofluorocarbons (HFCs) in a broader range of refrigeration and heating, ventilation, and air conditioning (HVAC) applications.

1.2 Objectives

The primary goal of the present study is to evaluate the fire hazard of R-290 (propane) in refrigeration appliances used in commercial retail and kitchen settings. The specific objectives are to: (1) perform a risk assessment to evaluate risk versus charge size; and (2) develop recommendations on how to prevent or mitigate the risks of using R-290 in commercial retail and kitchen applications.

1.3 Approach

Outlined below is the approach followed in the present study:

1) Identify flammability hazards associated with R-290 in commercial refrigeration applications
2) Identify parameters that influence likelihood and severity of these hazards
    a. Literature review
    b. CFD to confirm previous findings and dominating factors
    c. CFD to establish rulesets
3) Understand the environmental settings
    a. Geometries
    b. Ignition sources
4) Identify research gaps
5) Perform experiments to:
    a. Confirm the factors that impact the outcome of a leak
    b. Quantify severity
    c. Fill research gaps
    d. Test mitigation methods
    e. Validate CFD models
6) Assess risk quantitatively by:

a. Establishing failure modes and their effects
b. Establishing leak frequencies and ignition probabilities for different environments
c. Determining severity of events with CFD

7) Provide recommendations based on:
   a. Experimental and numerical findings
   b. Risk assessment results

2 Analysis

2.1 Current Standards and R-290 Charge Size Limits

It is helpful to review current charge size limits in relevant standards given that a primary objective of the present study is to evaluate risk versus R-290 charge size. Table 2.1 lists the standards providing guidance on the use of flammable refrigerants in commercial refrigeration appliances. ISO 5149 and EN378 provide charge size limits for use of A3 refrigerants in commercial refrigerated display cases in occupied spaces. Permissible charge sizes are based on the room volume where the display case is located and the lower flammability limit (LFL) of the refrigerant, and charge sizes are capped at a maximum of 1.5 kg (3.3 lb). UL 471 and IEC 60335-2-89 allow R-290 charges sizes up to 150 g (0.33 lb) for commercial refrigeration applications regardless of the volume of the room where the equipment is located. As such, the EPA has granted SNAP approval for R-290 charges up to 150 g (0.33 lb).

Table 2.1: International, domestic, and European Standards with guidance on the use of A3 refrigerants in commercial refrigeration applications.

Standard	Title	Application	HC charge size limits
UL 471	Standard for Commercial Refrigerators and Freezers	Commercial refrigeration appliances	Up to 150 g (0.33 lb)
IEC 60335-2-89	Particular requirements for commercial refrigerating appliances with an incorporated or remote refrigerant unit of compressor	Commercial refrigeration appliances	Up to 150 g (0.33 lb)
ISO 5149 and EN 378	Refrigerating systems and heat pumps - Safety and environmental requirements	All refrigeration, air conditioning, and heat pump applications; domestic, commercial, and industrial	Varies by access category and location classification: $M_{max} = 0.20 * LFL * A_{room} * h_{room}$ up to 1.5 kg (3.3 lb) in normally occupied spaces

2.2 Introduction to Hazard Analysis and Risk

Risk is the combination of likelihood of an event occurring and severity of this event. The likelihood of a combustion event is the likelihood of having the release and accumulation of fuel within a given space and a competent ignition source at the same time the fuel mixture is present.

The consequence of a combustion event is what happens after the fuel is ignited, and its severity can be rated by the degree of damage it causes to the facility/property or injury to humans.

One of the first steps in assessing the risk of R-290 in commercial refrigeration appliances is identifying the potential hazards associated with an accidental release of the refrigerant. Leaks can occur inside the conditioned space of a closed unit or external to the conditioned space of either an open or closed unit (i.e., in the room where the unit is located), and therefore the potential hazards when R-290 is released and ignited include:

1) Overpressures generated by the rapid expansion of the combustion products
2) Thermal radiation exposure
3) Direct flame exposure
4) Fragmentation of a glass or metal display case door due to internal deflagration

When there is a leak of a pressurized flammable fluid, such as R-290, there are two general outcomes that can result in the flammability hazards identified above: (1) when the flammable fluid is ignited and burns in the immediate plume of the leaking fluid, sometimes referred to as a flammable jet or a jet fire; or (2) when the flammable fluid builds up in regions remote from the leak and also burns in regions remote from the jet plume.

A flammable jet or jet fire is a turbulent diffusion flame, whereby the leaking fluid and air are not intimately mixed where the flame is burning. R-290 is stored and operated at elevated pressures within the equipment, hence when there is a loss of containment (e.g., hole), the fluid (vapor or liquid) is released at high velocity and momentum resulting in a "plume" of vapor. Air is entrained into the jet due to the high velocity and momentum of the released fluid relative to the air, and the plume is gradually diluted at a certain distance downstream the release. The left image in Figure 2.1 shows a pure fluid (represented as red) released horizontally that gradually dilutes to green then further to blue downstream from the release. The right image in Figure 2.1 shows an example of R-290 vapor being released horizontally from a 6-mm diameter hole forming a jet and a plume of fuel; the figure also includes a legend providing concentration, where red presents concentrations above the upper flammability limit (UFL or too fuel rich to burn) and blue at the LFL.

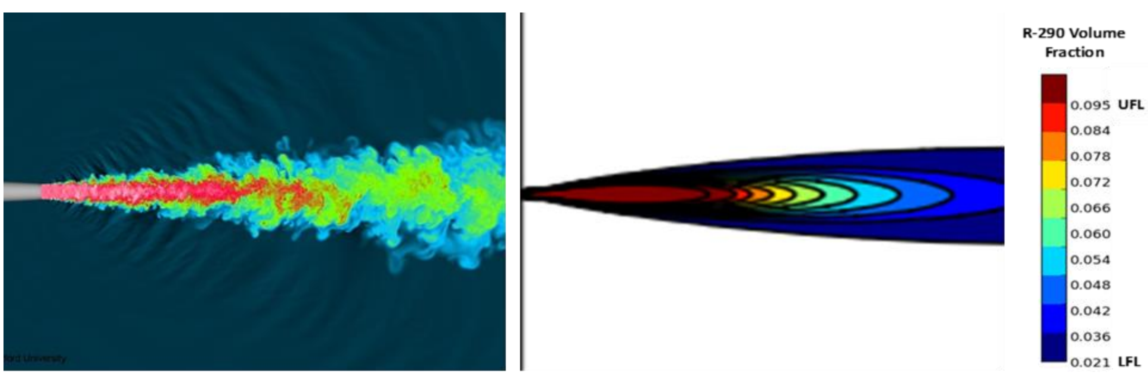


Figure 2.1: Left image is a sonic horizontal jet release, where the density of the pure fluid is red near the release, and gradually gets diluated with air as it goes to green then blue. The right image is the simulated concentration of a R-290 sonic release from a 6 mm (0.24 in) diamter hole, where dark red represents concentrations above the UFL and blue is at the LFL.

At the point of the release, the mixture is almost entirely fuel (seen as red in the images above). Downstream from the leak, the concentration of R-290 in the jet passes within its flammability limits and can be ignited. The flame will stabilize near this location, where the fuel and air can diffuse and combust at the flame front (see Figure 2.2). The volume of the R-290 plume, where the concentrations of the plume are greater than the LFL, is referred to the as the jet plume volume. As the leak rate is increased, the jet plume volume increases resulting in larger flammable jets. Flammable jets can only exist while a leak is occurring.

Figure 2.2: Jet flame example.

There are also times when a R-290 leak can build up to levels above the LFL in the space where the refrigerated display case is installed or inside the display case. The consequences of this flammability hazard are directly related to how the refrigerant disperses into a given space, or more specifically, how the released refrigerant mixes with the air in the space where the refrigerant is leaked. At one end of the spectrum, there may be releases for which the R-290 does not mix readily with air, resulting in "fuel rich" layers that are above the UFL. For example, if a high-pressure narrow jet is released and immediately impacts a surface (e.g., a release in the condensing unit housing that hits the housing wall), the fuel jet will lose its momentum and disperse away from the leak at a relatively low velocity. An example of these "fuel rich" layers is provided in Figure 2.3, which shows the R-290 concentration in a room while R-290 is leaked with low momentum at the bottom of a display case.

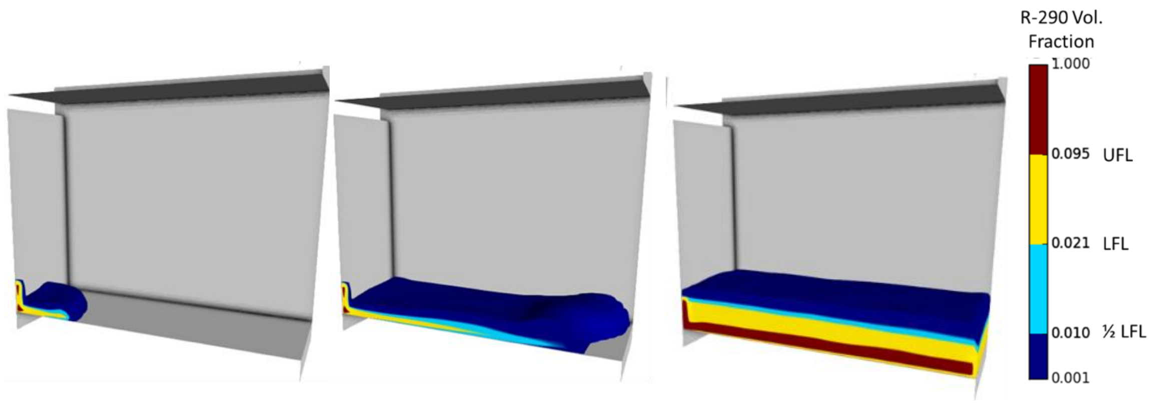


Figure 2.3: Example of a fuel rich layer resulting from a low momentum leak at the bottom of a display case (display case not shown). The left and middle images show the layer spreading across the floor, while the right image is the final fuel-rich layer.

These layers will have a region that is flammable near the interface of the fuel rich layer and air that, when ignited, will burn across the surface and then continue to burn the fuel in the layer below as a non-premixed diffusion flame (similar to a pool fire) as illustrated in Figure 2.4. The top images in the figure show a premixed flame (blue) propagating through the flammable layer (orange) after ignition. The bottom images show the rich layer (red) burning as a diffusion flame and entraining air once the premixed layer is consumed. The color bar at the bottom indicates the concentrations of the flue layers in the images on the left, with yellow, orange, and red representing layers with R-290 concentrations below, within, and above the flammability limits. The color box lengths are scaled to the concentration range of R-290 in each regime.

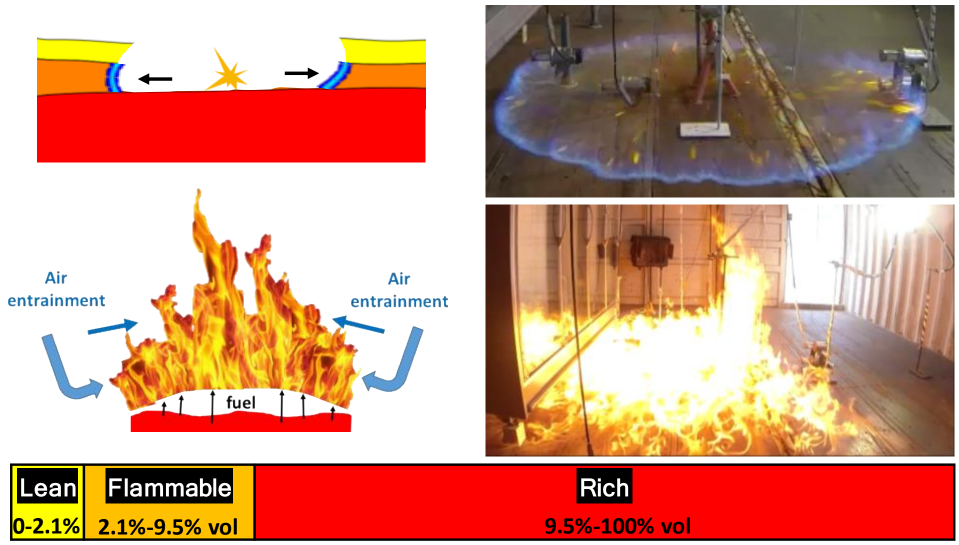


Figure 2.4: Example of how a "fuel rich" layer burns, where the top images show the blue flame burning across the flammable layer at the interface shortly after ignition and the bottom images show the rich lower layer subsequently burning as a diffusion flame.

At the other end of the spectrum of how the released refrigerant mixes, there may be releases where the R-290 and air intimately mix in a layer (or the entire space) to within the flammable limits (e.g., between the lower and upper flammability limits). A deflagration or flame front results when such a flammable volume is ignited, and continues to burn until the flammable mixture is consumed (see Figure 2.5 for an example). The images on the left illustrate a premixed flame (blue) propagating through a homogenous mixture of R-290/air within the flammability limits. The images on the right are actual images of what is depicted on the left, and the color bar at the bottom provides the concentrations below, within, and above the flammability limits. Note that while flammable jets can only exist while the leak is occurring, flammable volumes can persist in a room after the leak ends.

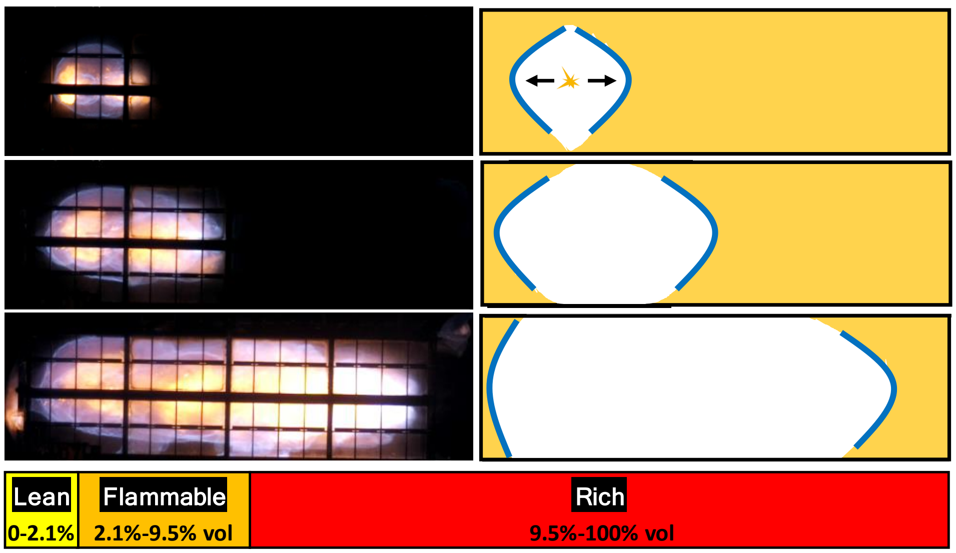


Figure 2.5: Example of how a premixed R290/air mixture filling an entire 50 m^3 room burns as a deflagration.

For this study, the term "jet plume volume" represents the fuel volume where R-290 concentrations are above the LFL in the plume of the leak, and upon ignition result in flammable jet or jet fires. In addition, the term "accumulated fuel volume" represents volumes of R-290 that have built up to concentrations above the LFL in a given volume. As discussed above, accumulated fuel volumes can encompass volumes ranging from fuel-rich layers (which when ignited burn across the surface and then as diffusion flames similar to pool fires) to well-mixed flammable volumes that result in deflagrations. As all of the fuel is consumed in both fuel-rich layers and well-mixed flammable volumes, they are both considered accumulated fuel volumes as the consequences of an ignition event are related to the available mass of R-290 that can burn.

The severity of the hazards identified above depend on the characteristics of the jet plume volumes and accumulated fuel volumes. For jet plume volumes, important characteristics include size of the plume and duration of the leak. For accumulated fuel volumes, important characteristics include size and concentrations of R-290 within the fuel volume. In terms of uniformity, fuel volumes can be homogeneous and flammable if R-290 is uniformly mixed between the LFL and UFL within the volume, or fuel-rich if R-290 is uniformly mixed above the UFL. Fuel volumes can be inhomogeneous, or layered, if R-290 does not mix uniformly in the space where it is leaked. Layered volumes contain varying concentrations of refrigerant and air, with R-290 concentration decreasing with height because it is denser than air. Both homogeneous and layered fuel volumes can range is size (or height) up to the entire volume of the space where the refrigerant is released.

Figure 2.6 outlines release scenarios, whether they form accumulated fuel volumes or jet plume volumes, and the hazards that exist when each is ignited. Note that while overpressures are typically associated with ignition of premixed clouds, they may also occur when fuel-rich layers are ignited as flame fronts can establish and accelerate through the upper refrigerant/air layer.

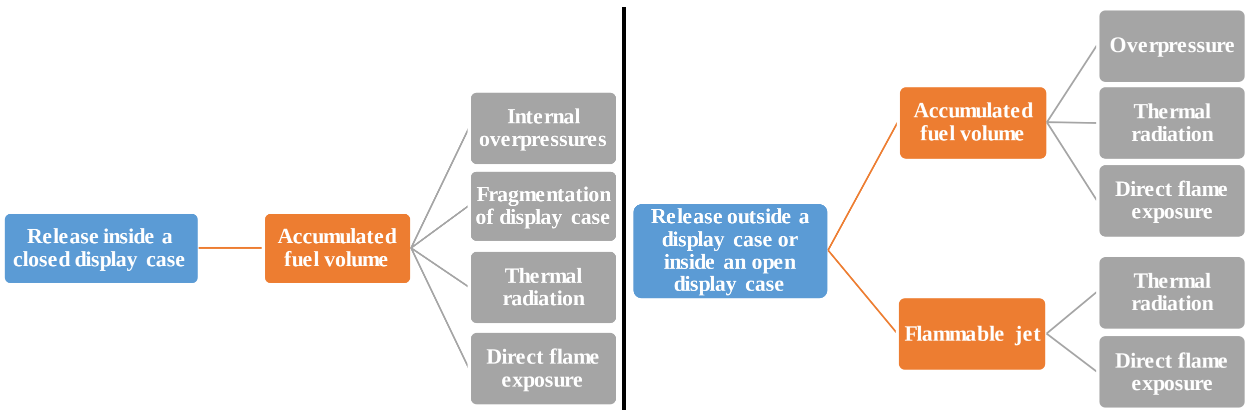


Figure 2.6: Types of releases (blue), types of flammable clouds or jets that can form from a release (orange), and the hazards that exist when the flammable clouds or jets are ignited (grey).

Assessing the risk of R-290 in commercial refrigeration applications requires an assessment of the likelihood of each release scenario, the likelihood of the formation and ignition of each fuel volume or jet plume, and the severity of each hazard associated with the ignition of each fuel volume or jet plume. Furthermore, it requires the identification of parameters that influence the likelihood and severity of these events. Important parameters have been identified in previous studies, thus the next section provides an overview of past findings.

2.3 Factors Affecting the Outcome of a Leak

Previous studies [1-13] have shown that the outcome of a leak depends on: (1) the properties of the leaked refrigerant; (2) leak conditions; (3) equipment properties; and (4) environmental aspects. CFD simulations were performed to further evaluate how certain of these properties affect how the fuel disperses and the resulting flammable hazard. This section introduces the important parameters and illustrates how they affect the outcome of a leak using results from CFD simulations.

Refrigerant properties

Density

The density of a refrigerant compared to the density of air dictates whether the leaked refrigerant will tend to migrate upward or downward under certain leak conditions. The larger the refrigerant density to air density, the higher the buoyant force driving the refrigerant toward the floor. R-290 is denser than air and therefore can accumulate near the floor for certain leak conditions.

Leak conditions

Leak velocity / momentum

R-290 leaks from a closed-loop vapor compression cycle will almost always initially have high velocity and momentum due to the high pressures within the system. The vapor pressure of R-290 even at ambient conditions is high enough to create sonic vapor jets and high velocity liquid jets. If a leak creates a free jet, which is a jet that does not impact a surface, then the velocity will remain sufficiently high to entrain air into the refrigerant jet, enhancing mixing with air and increasing dilution. In the present study, these types of releases are called jet or high momentum releases. In contrast, if a leak impinges on a nearby surface or obstruction, the velocity and momentum of the jet will be significantly reduced, resulting in inhomogeneous mixing in the space (since the release itself results in less mixing between refrigerant and air). For example, when leaks occur inside the condensing unit housing, the released jet can impinge on nearby surfaces or on the housing walls thus reducing the momentum of the release. In the present study, these type of impinged jet releases, which result in significant reduction of the release momentum, are referred to as a low momentum releases and are considered more likely than free jet releases since refrigerant containing parts are enclosed in most units.

Leak velocity affects how well the leaked refrigerant mixes with air in the space where it is released, and therefore affects the likelihood of a leak creating accumulated fuel volumes above the LFL. For example, high velocity leaks (high momentum) will more readily mix with air and increase dilution of the release. If the total quantities of fuel or charge sizes are properly limited for a given room volume, the homogeneous premixed environment resulting from a high momentum jet will not be flammable. In contrast, during low velocity leaks (low momentum), it is less likely that R-290 will mix with air and more likely that higher concentration fuel layers will form along the floor. These layers can have R-290 concentrations within or above the flammability limits, even when small charge sizes are used in large rooms, as the refrigerant spreads along the floor and only mixes with a small amount of the total room volume.

Figure 2.7 demonstrates how differently R-290 disperses during a high momentum (upper images) and low momentum (lower images) leak of 800 g from the bottom of a display case into a 48 m^3 (1695 ft^3) room. Images from left to right show the leaks progressing in time, specifically once 50 g (0.11 lb), 500 g (1.1 lb), and 800 g (1.76 lb) have been released.

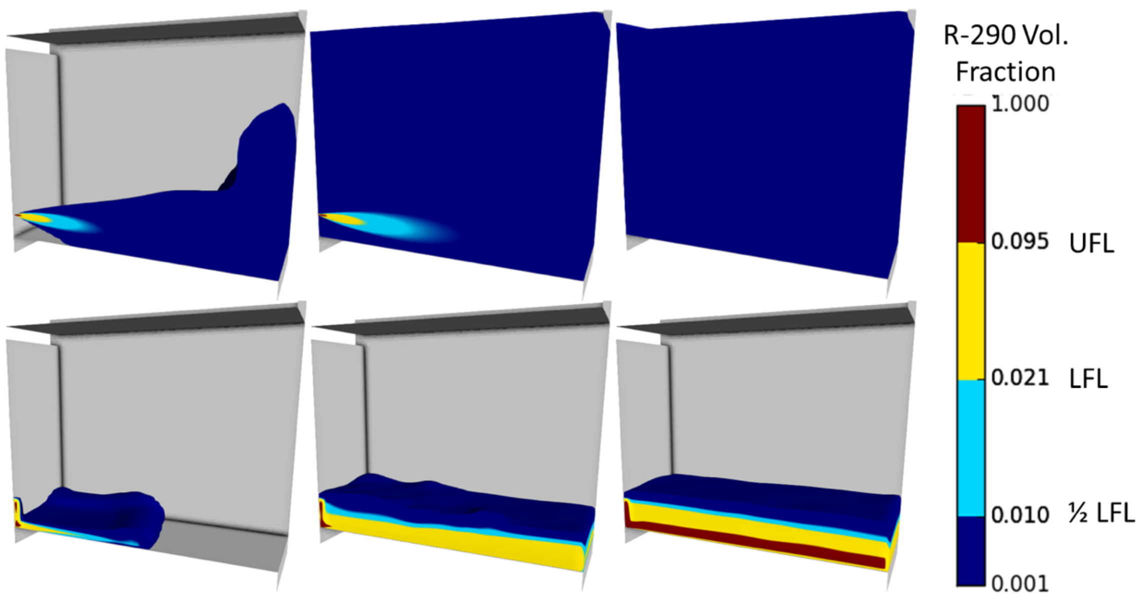


Figure 2.7: Dispersion of R-290 during a high momentum (top) and low momentum (bottom) release.

Leak location in the refrigeration cycle

Leak location dictates the phase of the refrigerant at the leak site since the refrigerant in a vapor compression cycle exists as a vapor, liquid, and two-phase mixture depending on where it is in the cycle (see Figure 2.8). For example, the refrigerant is a liquid between the condenser and expansion valve and is a vapor between the evaporator and compressor.

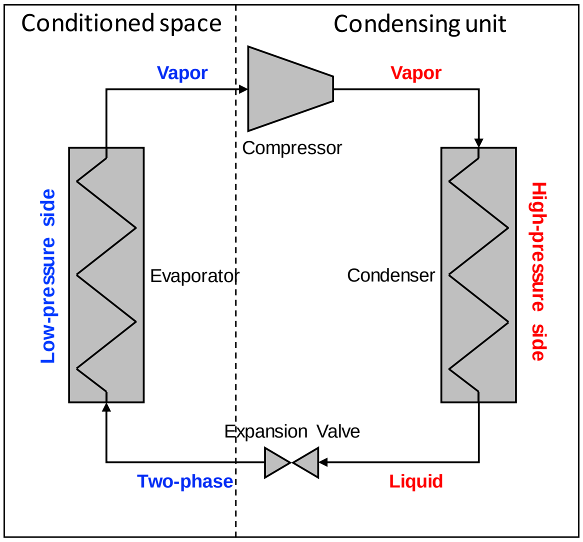


Figure 2.8: Simplified diagram of a vapor compression cycle illustrating the refrigerant phase at different stages of the cycle.

Liquid releases have a mass flow rate roughly seven times higher than vapor releases when leaked through the same hole size and with the same upstream pressure (discussed further in Section 2.5). Furthermore, a leak of liquid R-290 from a refrigeration cycle will result in a "flashing" liquid release because the boiling point temperature at ambient pressure is much lower than typical ambient temperatures. During a flashing liquid release from a refrigeration cycle, a certain fraction of the released liquid will immediately vaporize (i.e., the initial flash fraction) and if the jet is unobstructed, the remaining droplets will continue to vaporize as air is entrained into the jet (left frame of Figure 2.9). If a flashing liquid release impinges on a surface, the droplets remaining after the initial flash can "rain out" and form a pool due to the reduced air entrainment affecting the evaporation rate of the droplets (right frame of Figure 2.9).

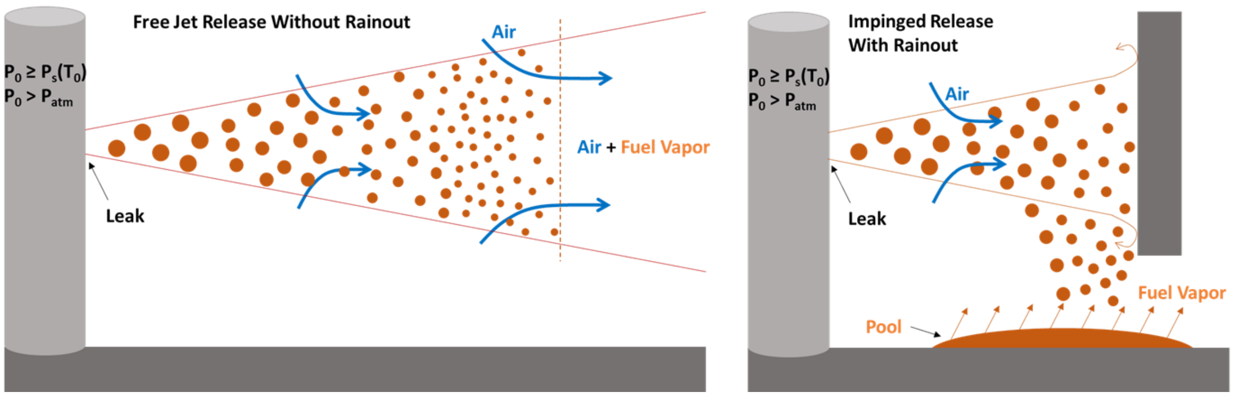


Figure 2.9: Flashing liquid release vaporizing and mixing with air (left image) and impinging on a surface and raining out (right image).

While a flashing liquid release is physically different from a high momentum vapor release, for the present study, the two jet releases are assumed to result in relatively homogeneous mixing at some distance remote form the release. For example, if the velocity of the flashing liquid jet is sufficiently high to entrain air into the refrigerant jet, this will enhance mixing with air and increase dilution, and again, if charge sizes are properly limited for a given room volume, the homogeneous premixed environment resulting from a free flashing jet will not be flammable. In contrast, if a flashing liquid release impacts a nearby surface, the momentum (and mixing) will be lost and a fraction of the liquid droplets will rain out and form a liquid pool. The low momentum release will have components of both low velocity vapor and evaporation from the liquid pool. For the purpose of this study, it is assumed that any liquid pooling of R-290 vaporizes quickly and conservatively contributes immediately to the vapor dispersion.

Leak location is also important because portions of the cycle are either internal or external to the conditioned space. Internal leaks from the low-pressure side can result in R-290 accumulation inside the conditioned space, while external leaks from the high-pressure side can result in R-290 accumulation in the space where the display case is located.

Physical leak location – condensing unit location

The location of the condenser portion of the circuit influences the likely height of a leak at this part of the circuit. Condensing units can be located at the top or bottom of a display case. Leak location is important in terms of height from the ground especially for low momentum external leaks. For low momentum releases that are located near floor level, R-290 will tend to form high concentration layers that spread radially from the leak source along the floor (see Figure 2.10). As the height of the release location increases, so does the distance the heavier-than-air R-290 must travel as it "falls" toward the floor. When the R-290 travels downward, it mixes to some degree with the air (see Figure 2.10) and tends to form layers at the ground with lower concentrations than releases near ground level. In each column of images the elapsed time from the start of the leak and the amount of mass released are the same.

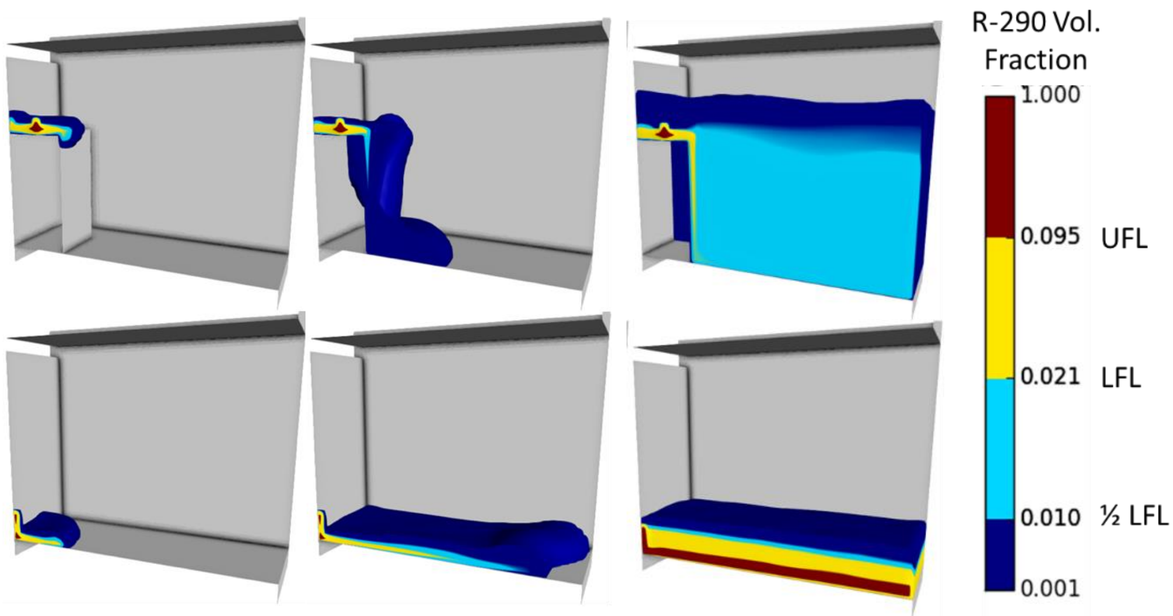


Figure 2.10: Low momentum release at the top of display case (top images) falling toward the floor and mixing with air and low momentum release at the bottom of a display case spreading along the floor (bottom images).

Figure 2.11 demonstrates the different fuel layers that form when a low momentum leak of 600 g (1.32 lb) occurs at the condenser when mounted at the bottom (left image) or top (right image) of a display case in a 60 m^3 (2119 ft^3) room when the condenser fan is off with a leak rate of 120 g/min (0.26 lb/min). The figures show the R-290 concentration along an elevation cut-plane through the leak. The leak near the floor creates significantly higher R-290 concentrations along the floor up to a height of 0.5 m (1.64 ft), whereas the leak above the display case creates concentrations above the LFL only at the top of the unit and along the sides because the R-290 mixes with air as it "falls" downward toward the floor creating a more diluted layer with a height of over 1.0 m (3.28 ft) for the displayed concentration range. Note that both frames in Figure 2.11 show the concentration of R-290 at the end of the leak.

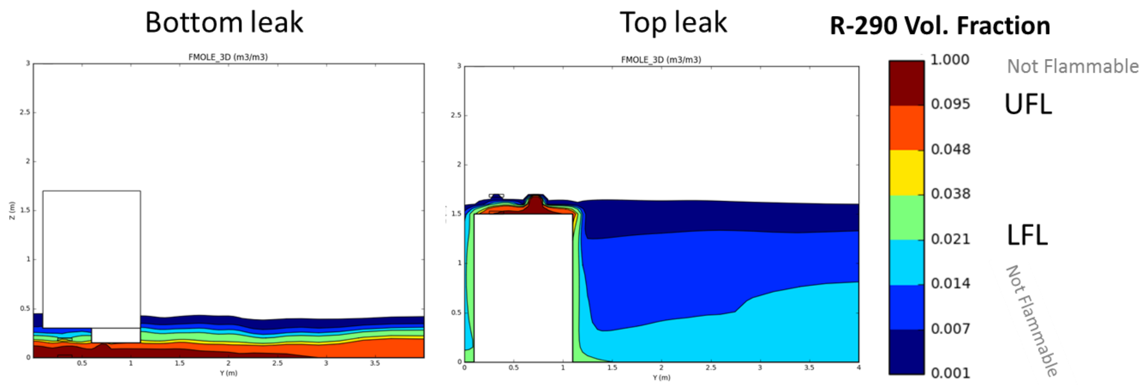


Figure 2.11: R-290 concentrations resulting from a low momentum leak at the condenser when mounted at the bottom (left) or top (right) of a display case. The figures show the vertical variation in R-290 concentration at a room depth equal to the leak location.

For high momentum releases, the leak is dominated by convection as opposed to buoyancy, thus resulting in more homogenous mixtures throughout the room with less dependence on release height.

Leak mass flow rate

Regarding flammable jets or jet fires, the size of the jet plume during an R-290 release is directly correlated to the size of the leak or the leak mass flow rate (see Figure 2.12). As the leak mass flow rate increases, the resulting volume of the jet plume increases and therefore so does the size of the flammable jet when ignited.

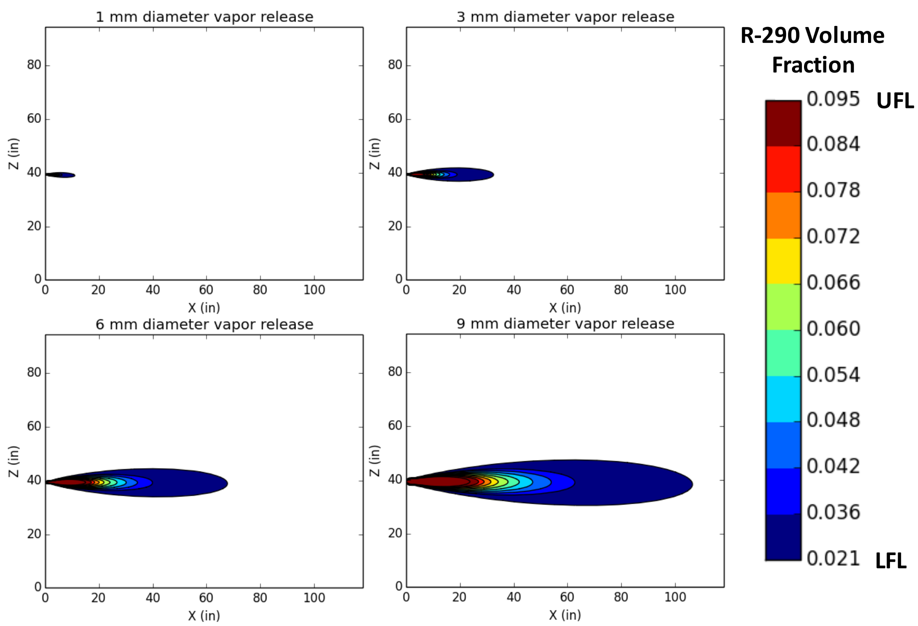


Figure 2.12: Jet plume sizes for 1 mm (0.04 in), 3 mm (0.12 in), 6 mm (0.24 in), and 9 mm (0.35 in) diameter vapor releases.

If the total quantities of fuel or charge sizes are properly limited for a given room volume, the homogeneous premixed environment downstream the localized high momentum jet will not be flammable, and for all intents and purposes, fairly independent of the potential leak mass flow rate. Note that there still will be a flammable jet plume local to the leak and the size of the plume is proportional to the leak rate as discussed in Section 2.2.

For low momentum releases near the floor level, assuming no natural or mechanical ventilation are present in the space where the display case is installed, the only mixing mechanism is diffusion of R-290 upward from the layer that forms at the floor. Therefore, at the end of the leak duration when the same amount of R-290 is released (i.e., charge size), lower leak rates will result in layers slightly taller and with lower concentrations at the floor (see Figure 2.13) as there is more time during the leak (i.e., longer leak duration) for R-290 to diffusively mix. For example, a 10 g/min (0.02 lb/min) release for a 600 g (1.32 lb) charge size will take 60 minutes to completely discharge the mass at a constant release rate, whereas it only takes 2.4 minutes for a 250 g/min (0.55 lb/min) release. Note that Figure 2.13 shows the concentration of R-290 at the end of each leak (i.e., 60 min and 2.4 min respectively).

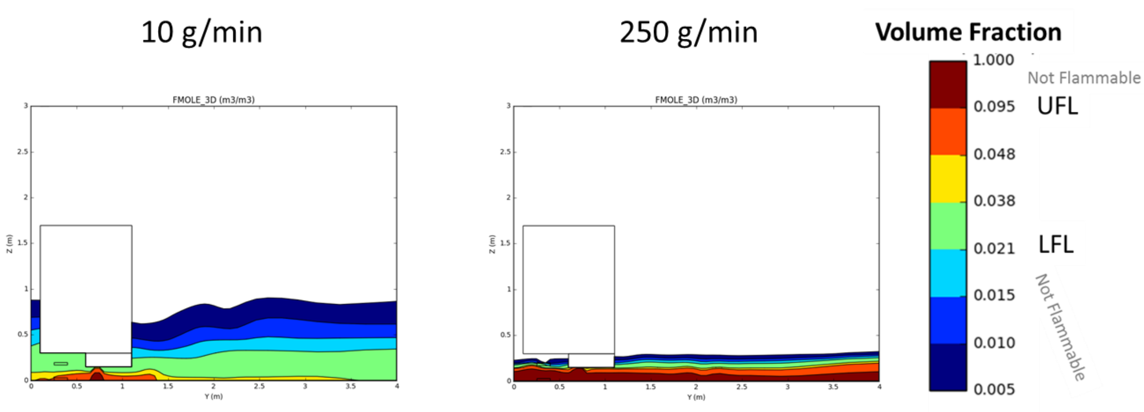


Figure 2.13: R-290 concentration for a low momentum leak at the bottom of a display case at a leak rate of 10 g/min (0.02 lb/min) and 250 g/min (0.55 lb/min).

For low momentum releases at the top of the display case, the mass flow rate also influences the amount of mixing as R-290 travels downward due to buoyant forces. For example, higher mass flow rates result in less overall mixing with air and higher concentrations at the floor, hence larger accumulated fuel volumes. As illustrated in Figure 2.14, when releasing 600 g (1.32 lb) from the top of the display case into a 60 m^3 (2119 ft^3) room, a leak of 250 g/min (0.55 lb/min) results in flammable layers along the floor whereas a leak of 10 g/min (0.02 lb/min) only results in concentrations exceeding the LFL near the leak. Note that Figure 2.14 shows the concentration of R-290 at the end of each leak (i.e., 60 min and 2.4 min respectively).

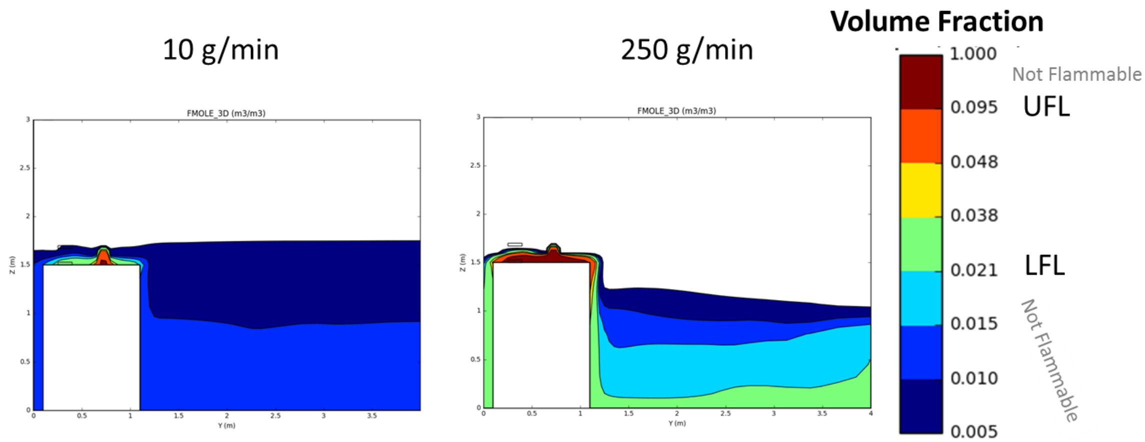


Figure 2.14: R-290 concentration for a low momentum leak at the top of a display case at a leak rate of 10 g/min (0.02 lb/min) and 250 g/min (0.55 lb/min).

Leak mass flow rate – transient versus constant leaks

Leak mass flow rates are dictated by the following factors: (1) hole size from which the leak occurs; (2) phase of the fluid at the release; and (3) pressure and temperature of the fluid. For R-290 systems not in operation (compressor is off), both liquid and vapor propane are in equilibrium in the system. At room temperature of 20 °C (68 °F), the vapor pressure at these conditions is 7.35 barg (107 psig). At these pressures, if the leak occurs on the vapor side it would result in a sonic velocity release at the orifice; however, on the liquid side, it would result in a high pressure incompressible liquid release. The details of such releases will be discussed later; however, it is worth noting that at equal pressures, the liquid release is approximately seven times higher than the vapor release for the same hole size.

When the leak occurs on the vapor side, the liquid in the system vaporizes to essentially "replenish" the vapor lost during the leak. This vaporization takes energy from the system and, depending on the leak rate, can cool the liquid and vapor within the system. For example, during a very small leak on the vapor side, the rate of liquid vaporization in the system will be slow enough that the refrigerant will remain at nearly the same temperature and pressure as the rate of heat removal due to vaporization is balanced by the rate of heat transferred into the refrigerant from the environment. In contrast, if the leak is large enough, significant cooling can occur in the liquid and to the system (i.e., frost is observed on the pipes) as the heat transfer from the environment cannot keep up with the rate of heat removal due to the higher vaporization rate. The evaporative cooling, which is a function of the system and leak rate, will also decrease the pressure—and as the pressure decreases, the leak rate will also decrease.

Figure 2.15 shows an example demonstrating the differences between a constant 240 g/min (0.53 lb/min) leak rate for a 1000 g (2.2 lb) charge size (assuming negligible evaporative cooling) and a transient leak rate (assuming evaporative cooling) initially starting at 240 g/min (0.53 lb/min) for the same charge size. It should be noted that this example was not for an actual refrigeration system, hence the transient behavior may differ for an actual system. The leak rate can decrease dramatically during the vapor release as a result of evaporative cooling and hence would affect the consequences of such a release. This example is for evaporative cooling that occurs during a release from a tank as opposed to an operating, closed-loop refrigeration system—which is a less complex example and is likely a less drastic change in leak rate. The effects of evaporative cooling during leaks in actual refrigeration systems are extremely complex (especially when accounting for the work done by the compressor when operating), and therefore, for the purposes of this study, it is conservatively assumed that all vapor leaks remain at a constant leak rate.

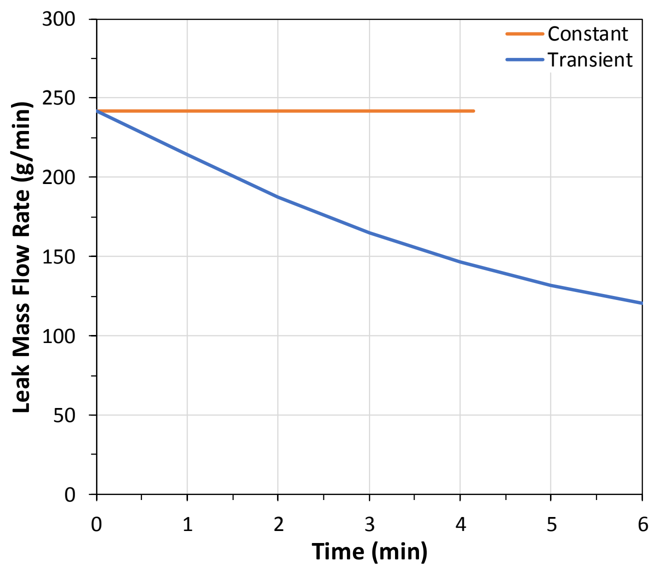


Figure 2.15: Decrease in mass flow rate during a 1000 g (2.2 lb) vapor release due to evaporative cooling. Data from experiment described in ref. [14].

Regarding liquid leaks, the resulting release would be a flashing liquid release and much of the evaporative cooling would occur external to the system. However, as the quantity of liquid decreases, natural depressurization of the system can occur. Similar to a vapor release, the effect of the work performed by the compressor increases the complexity of the problem. Hence, for the present study, it is conservatively assumed that all liquid leaks remain at a constant leak rate.

Equipment properties

Charge size

As the charge size increases, so does the amount of R-290 that can be released and contained in accumulated fuel volumes. Therefore, considering all other leak characteristics being equal (e.g., leak rate, leak location, momentum, fluid, etc.), leaks from larger charge sizes result in larger accumulated fuel volumes, which when subsequently ignited, generally result in more severe consequences.

Refrigerant charge size must be considered in reference to room size so that a leak does not result in a flammable premixed cloud that fills a large volume of a given room as the potential severity resulting from a premixed deflagration is high. Based on the density of R-290 and the concentration of mass per unit volume at the LFL (0.038 kg/m^3 or 0.00237 lb/ft^3), charge sizes can be limited to avoid premixed flammable clouds from filling an entire room or a significant fraction of the room (e.g., ¼ room volume). Figure 2.16 shows the results of two jet releases that homogenously mixed in the entire volume of a 48 m^3 (1695 ft^3) room, where one is the release of 2.7 kg (5.95 lb) resulting in a flammable mixture above the LFL (left image), and the other is the release of 455 g (1.0 lb) resulting in a non-flammable mixture at approximately ¼ LFL (right image).

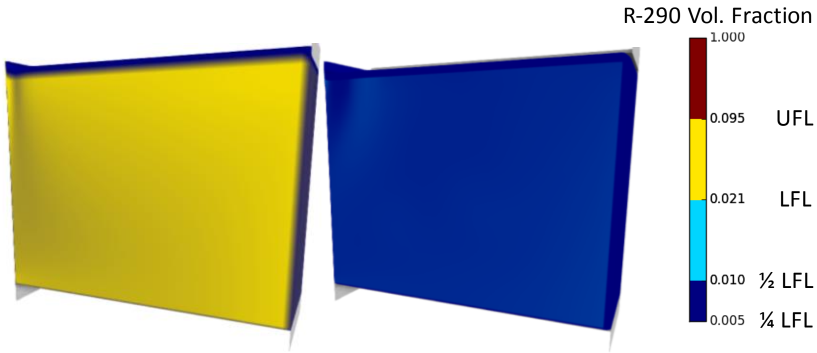


Figure 2.16: Left and right frame show the homogeneously mixed environment from a jet release of 2.7 kg (5.95 lb) and 445 g (1.0 lb).

Similarly, the left and right frames of Figure 2.17 demonstrate the significant increase of the fuel-rich layer when the charge size of a low momentum R-290 release at the bottom of a display case in a 60 m^3 (2119 ft^3) room was increased from 150 g (0.33 lb) to 1000 g (2.2 lb).

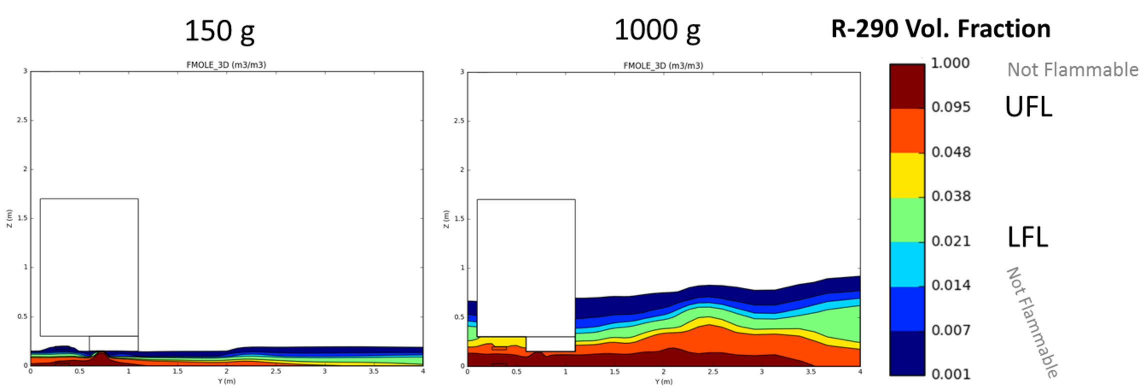


Figure 2.17: Difference in accumulated fuel volumes for a 150 g (0.33 lb) and 1000 g (2.2 lb) release from the bottom of a display case in a 60 m^3 (2119 ft^3) room.

Whether the display case is open or closed

Open display cases have no physical barrier between the conditioned space and the environment whereas closed cases do. Open display cases typically require a larger charge size than closed cases to cool the same amount of internal volume due to the higher air change rate in the conditioned space. Free jet releases inside an open display case will have similar outcomes to free jet releases outside of the conditioned space. Low momentum releases inside an open display case could cause R-290 to accumulate in the lower section of the conditioned space. The likelihood of R-290 accumulating in an open display case depends on the design (i.e., the depth of the conditioned space compared to the height of the containing walls) and also the amount of items in the display case.

When a high or low momentum leaks occur in a closed display case, the entire released charge can accumulate in the case and disperse all at once into the room where the case is located once it is opened. This is a potentially high severity scenario exclusive to closed display cases and therefore the experimental work and risk assessment that follow focus on closed display cases.

Figure 2.18 demonstrates what would happen if a leak occurred inside a closed display case and the door was opened soon after the leak ended. In this simulation, 900 g (1.98 lb) of R-290 was released with low momentum inside a 2.44 m (8 ft) wide closed display case located in a 33.3 m^2 (359 ft^2) room. Provided in each frame is the time from when the cabinet was opened, demonstrating that the mixture volume largely dissipates within about 20 seconds. The dispersion of the mixture into the room when the door is opened is similar to a low momentum release at approximately the mid-height of the display case. There is an intermediate amount of buoyancy-induced mixing, compared to low momentum bottom or top releases, that dilutes the accumulated fuel volume as it spreads into the room. Note that high momentum releases inside the display case result in homogeneous mixing in the entire internal volume; however due to the charge size, the resulting mixture in the cabinet is fuel rich and therefore disperses from the cabinet similarly to the mixtures created by low momentum releases.

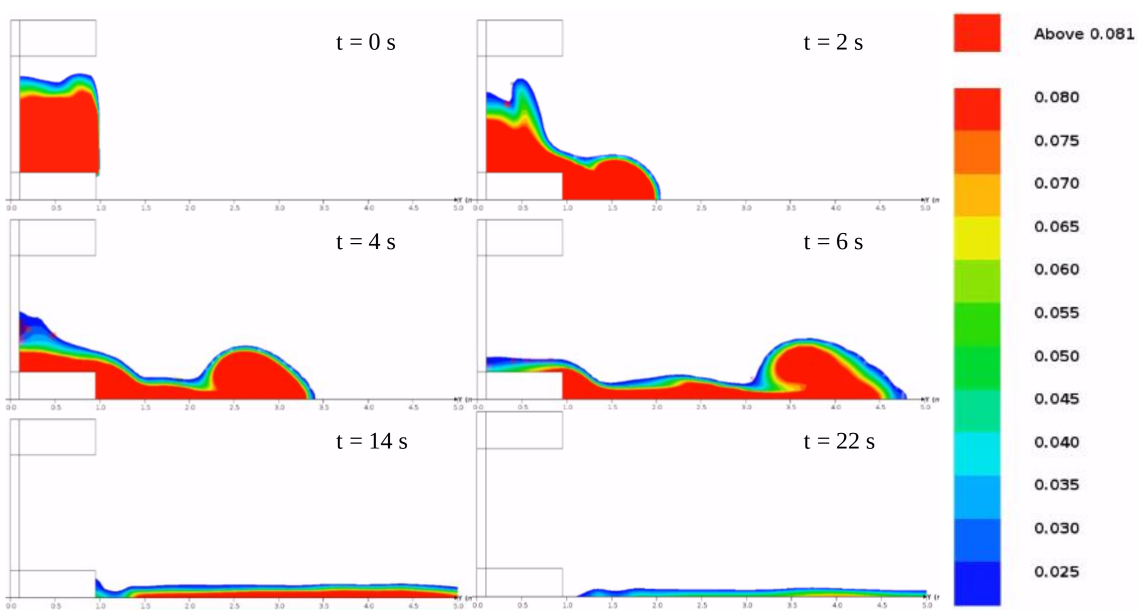


Figure 2.18: Accumulated fuel volume exiting a 2.44 m (8 ft) wide closed display case after 900 g (1.98 lb) of R-290 were released inside, followed by one the opening of one of the doors.

Whether the condenser or evaporator fan is on when a leak occurs

Unit airflow is created by the condenser fan and/or the evaporator fan. Mechanically driven air circulation from a fan housed within a display case can result in additional mixing, more homogeneous environments, and lower peak concentrations. This is especially true for low momentum releases that tend to minimally mix with air and form fuel-rich layers. The presence of the mechanically driven airflow induces mixing and can help maintain fuel levels below the LFL (assuming that the charge was appropriately sized for the room volume).

Figure 2.19 demonstrates the difference in mixing when a low momentum leak of 600 g (1.32 lb) occurs at the bottom of a display case in a 60 m^3 (2119 ft^3) room, at a leak rate of 120 g/min (0.26 lb/min) with the condenser fan off (left image) or on (right image). As seen in the figure, fuel-rich layers form at the floor when the condenser fan is off. Conversely, a homogeneous premixed cloud below the LFL fills the entire room when the condenser fan is on (note the charge size was scaled properly).

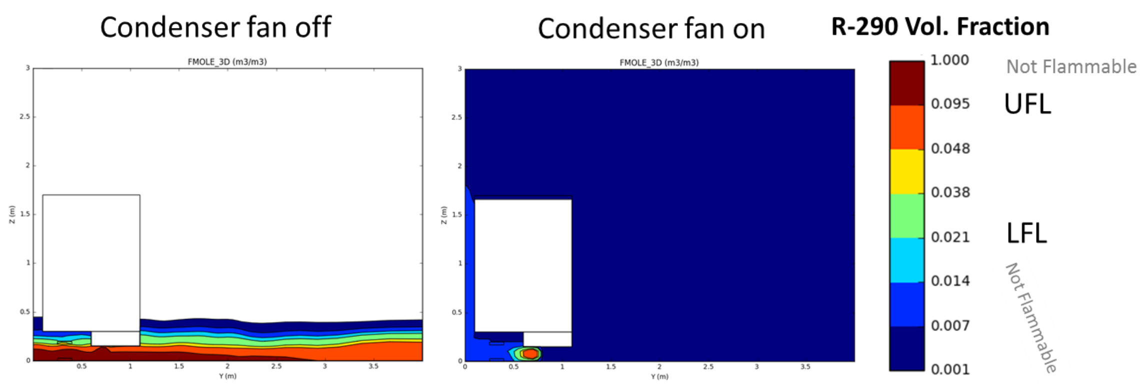


Figure 2.19: R-290 concentration for a diffuse leak at the bottom of the display case without (left) and with (right) the condenser fan in operation.

Cabinet tightness

For closed cabinet units, a completely sealed cabinet results in a larger amount of R-290 remaining inside the cabinet after an internal leak compared to a cabinet that is not completely sealed, as for the latter, R-290 can leak out of the cabinet. The present study does not evaluate the influence of the cabinet tightness on the outcome of a leak. Cabinets are conservatively assumed to be completely sealed and the released fluid cannot escape or be diluted while the door is closed. In addition, it is also assumed that the full charge is released into the cabinet prior to opening.

Environmental aspects

Room size

For the same amount of refrigerant released, smaller room sizes generally result in higher concentrations since there is less volume of air to mix with and dilute the released refrigerant vapors.

Room tightness

A completely sealed room results in higher concentrations compared to, for example, a room with a gap beneath a door. Less air infiltration results in less available air to mix with and dilute the released refrigerant vapors. The present study does not evaluate the influence of room tightness on the outcome of a leak. Rooms are conservatively assumed to be completely sealed.

Room ventilation

In many commercial structures, mechanical ventilation and airflow (typically measured in air changes per hour) are required in occupied spaces to assure acceptable indoor air quality. This is especially true in commercial kitchens. Room ventilation results in lower concentrations by enhancing mixing with air to dilute the released refrigerant vapors. For example, it is expected that mechanical ventilation would have a significant impact on low momentum releases with low leak rates occurring from refrigerated display cases as mechanically induced airflow will have a higher impact on diluting such releases. In addition, for large releases, mechanical ventilation can help decrease the time that the accumulated fuel volumes remain present in a room.

The present study does not consider the influence of room ventilation on the outcome of a leak as this is outside the current scope of the project and would be outside of the control of cabinet manufacturers to ensure proper room ventilation levels. Therefore, rooms are conservatively assumed to have no ventilation.

2.4 Establishing Rulesets for the Risk Assessment

Preliminary CFD simulations confirmed how certain factors affect the outcome of a leak and identified leak conditions and scenarios that do not create flammable plumes and ignitable volumes. Based on the extensive simulations performed and discussed above, certain rulesets can be established to more efficiently perform the risk assessment.

Ruling out risk of homogeneous premixed atmospheres exceeding the LFL

Limiting charge size based on room volume is an effective technique to mitigate the formation of homogeneously mixed flammable volumes that fill the entire room where a leak occurs. Based on the density of R-290 and the concentration of mass per unit volume at the LFL (0.038 kg/m^3 or 0.00237 lb/ft^3), the charge size necessary to avoid premixed flammable clouds from filling an entire room can be determined. If this technique is followed, homogeneously mixed room environments will remain below the LFL. Moreover, impinged jets may result in partial mixing and accumulated fuel layers (as opposed to mixing within the entire room), hence a factor of safety such as ¼ LFL may be used or equivalently 0.0095 kg/m^3 (0.00059 lb/ft^3) for R-290.

Ruling out the formation of accumulated fuel layers above LFL from free jet releases

Free jet or high momentum releases create enough mixing to yield near-homogeneous environments when leaked into a room, and thus fuel volumes do not accumulate at the floor, even when a release occurs near the floor.

This is demonstrated in Figure 2.20, which provides CFD results of R-290 concentrations in a room when leaked near floor level through a 3 mm (0.12 in) and 9 mm (0.35 in) orifice. The leftmost and center images are while the leaks are still occurring and thus higher concentrations are seen in the respective jet plumes near the floor. The rightmost images are shortly after the 455g (1.0 lb) release ends (mass corresponding to 25% LFL for the entire room volume).

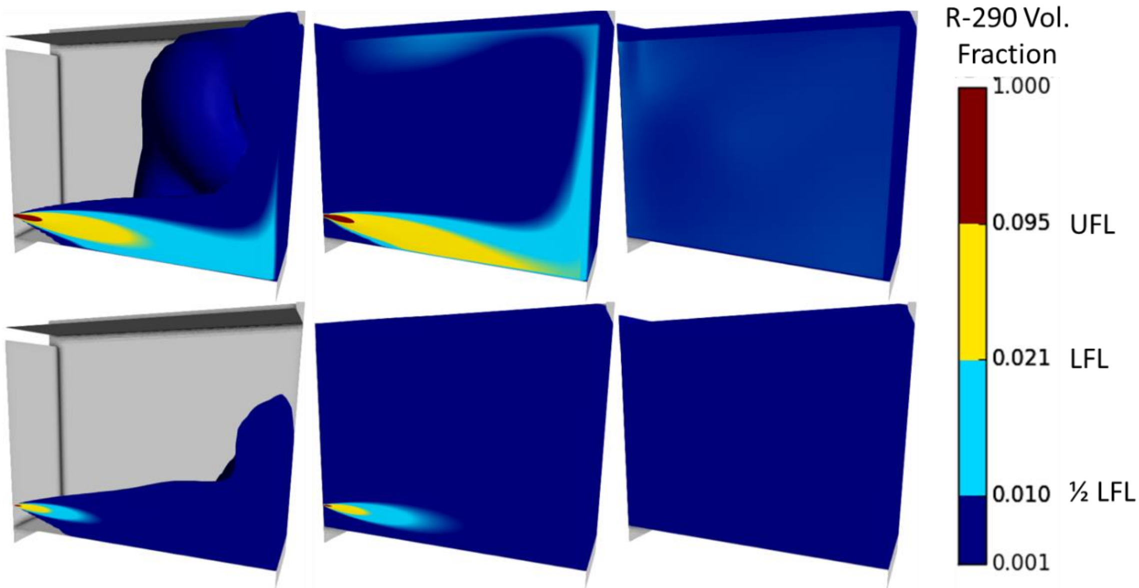


Figure 2.20: Top and bottom frames show a vapor jet release through a 9 mm (0.35 in) and 3 mm (0.12 in) diameter orifice. The entire room volume is homogeneously mixed at approximately ¼ LFL.

Ruling out jet fire risk for small diameter vapor releases

The size of the jet plume volume depends on the leak diameter as previously shown in Figure 2.12, the phase of the refrigerant at the leak, and the pressure difference across the leak. Free jet or high momentum releases with a high enough leak rate or large enough leak diameter may create non-negligible jet plume volumes during a release. As discussed in Section 2.2, the hazard associated with these volumes is a flammable jet or jet fire, and is distinct from accumulated fuel volumes forming in the space where a refrigerant is leaked.

Free jet or high momentum releases through small diameter holes have flammable jet volumes that extend no more than a few inches from the leak. CFD simulations show (see Figure 2.12) that a free jet vapor release through a leak diameter of 1 mm (0.04 in) creates a flammable jet volume that extends 28 cm (11 in) from the leak during the release. Once ignited, the flame will stabilize somewhat closer to the leak location where the R-290 and oxygen from the air diffuse to near stoichiometric concentrations. Therefore, small vapor leaks of 1 mm (0.04 in) or less in diameter do not create jet fire hazards. Note that our estimations indicate that 99% of all leaks occur through hole sizes less than or equal to 1 mm (0.04 in), as discussed further in Section 5.4.1.

Ruling out a jet fire hazard during impinged releases

When a leak impinges on a surface, there is no flammable jet that forms and therefore there is no possibility of a jet flame, hence accumulated fuel volumes are the only resulting hazards.

Graphical Illustration of Ruled-out Hazards

Figure 2.21 provides a graphical illustration of the scenarios and hazards ruled out by preliminary CFD simulations. In the figure, the hazard analysis of Section 2.2 is extended to include free jet and impinged jet releases in the different identified scenarios. The accumulated fuel volumes and jet plumes ruled out are crossed out in red and flammable jets from free releases now only need to be considered for all liquid releases and vapor releases when leak diameters are ≥ 1 mm (0.04 in).

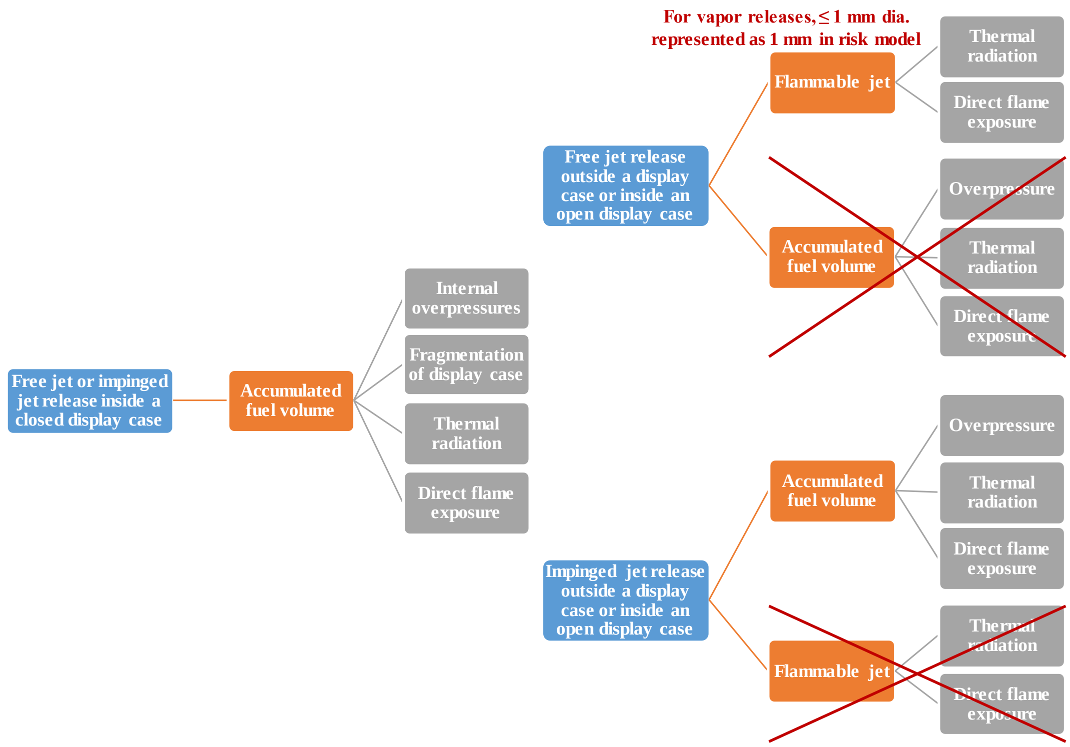


Figure 2.21: Extension of Hazard Analysis to include free jet and impinged releases in the different identified scenarios. Flammable cloud/jet types ruled out for different scenarios are crossed out in red. Flammable jet hazards have been ruled out for vapor leaks with ≤ 1 mm (0.04 in) diameter.

These preliminary findings limit the scenarios remaining in Figure 2.21 that need to be studied in further detail as part of the risk assessment in Section 5.

2.5 Leak Mass Flow Rate vs Leak Hole Size

As previously discussed, mass flow rate is an important parameter that influences the outcome of a leak and can be determined based on the hole size and the refrigerant phase, temperature, and pressure at the leak site.

ISO 5149 establishes conservative maximum pressures in the high- and low-pressure sides of a refrigeration cycle operating on R-290 (see Table 2.2). The pressures are equivalent to the vapor pressure of R-290 at the conceivably highest temperatures the refrigerant could reach on the high- and low-pressure sides (dependent on external temperatures). The high-pressure side temperature is during operation and the low-pressure side temperature is during idle conditions.

Table 2.2: Table of maximum pressures and temperature recommended in BRA Code of Practice 2014 and in accordance with EN378-1:2008 A2:2012.

Max Pressure, barg (psig)		Max Temperature, °C (°F)	
Low side	High side	Low side	High side
10.3 (149)	18.1 (263)	32 (90)	55 (131)

When establishing leak rates as a function of hole size, vapor releases are considered on the high- and low-pressure sides (condenser and evaporator sides respectively) and liquid releases are considered on the high-pressure side (condenser side). Two phase releases on the low-pressure side are assumed to have the mass flow rate of pure liquid releases (as discussed in further detail below, the outcome of leaks on the low-pressure side, inside the cabinet, is relatively insensitive to mass flow rate thus this assumption minimally impacts the results of the risk study). Vapor mass flow rates are determined using Eq. 1, which is the equation for choked flow of a gas through an orifice:

$$\dot{m} = C_d A_0 \sqrt{\gamma \rho_g P_1 \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{1}$$

where C_d is discharge coefficient (assumed to be 0.85 for vapor phase releases), A_0 is the area of the orifice, γ is the specific heat ratio, ρ_g is the upstream gas density, and P_1 is the upstream pressure.

Liquid mass flow rates are determined using Eq. 2, which is the equation for incompressible flow through an orifice:

$$\dot{m} = C_d A_0 \sqrt{2\rho_{liq}(P_1 - P_{atm})} \tag{2}$$

where C_d is discharge coefficient (assumed to be 0.62 for liquid phase releases), A_0 is the area of the orifice, ρ_{liq} is the liquid density, and P_1 is the upstream pressure. Note that when a leak occurs on the liquid side, R-290 begins to flash evaporate just upstream of the orifice, thus the estimation of mass flow rate using incompressible flow is conservatively high, but reasonable. Figure 2.22 provides the mass flow rates for vapor and liquid releases through various diameter leaks when occurring on the high- and low-pressure sides of a cycle as determined using Eqs 1 and 2 and the conditions given in Table 2.2.

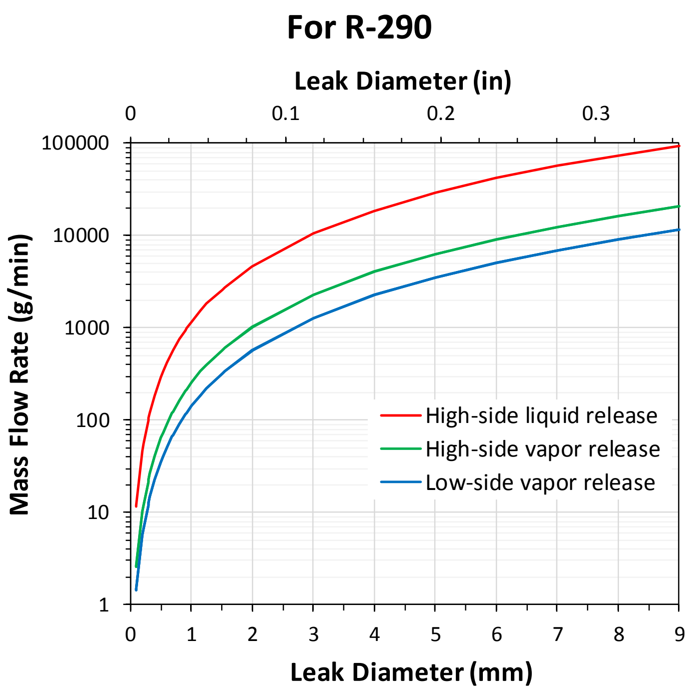


Figure 2.22: Mass flow rate as a function of leak diameter for vapor released from the low-pressure side (blue curve), vapor released from the high-pressure side (green curve), and liquid released from the high-pressure side (red curve).

2.6 Gap Analysis

Gexcon identified gaps in previous studies that were publicly available and addressed them in the present study as part of assessing the risk of R-290 in commercial refrigeration applications. The gaps are presented below as those associated with the likelihood of an event and the consequence of an event.

Likelihood Gaps

Previous studies focused on different leak hole sizes and leak rates, with smaller leaks generally considered in risk assessments performed in Europe for the use of A3 refrigerants. In most of the European studies with R-290, leak diameters considered were on the order of 1 mm (0.04 mm) or smaller and leak mass flow rates were at most 60 g/min (0.13 lb/min). In domestic risk assessments with A2L refrigerants, sub-millimeter leaks received less focus and leak diameters up to 9.5 mm

(0.37 in) were considered with flow rates as high as 1800 g/min (3.97 lb/min). In principle, leak sizes and their corresponding frequencies of occurrence are independent of the refrigerant working fluid and dependent on equipment details, such as length and diameter of piping and the number of flanges, valves, etc. in the system. Therefore, the current study applies a more unified approach that builds on previous domestic risk assessments on the use of A2L refrigerants and previous European risk assessments on the use of A3 refrigerants.

While only considering small hole sizes is partially justified from a frequency standpoint (discussed further in Section 5.4.1), a complete risk assessment should:

- Include larger leaks despite their lower likelihood of occurring because of their severity, and
- Demonstrate that despite the higher consequences of larger leaks, the overall risk may still be very low after accounting for the likelihood of those leaks and their ignition.

Another aspect receiving limited attention in past studies is the refrigerant phase when leaking from a unit. In general, previous studies have not established differences in risk for a vapor release and a flashing liquid release. As discussed above, the state of the refrigerant as it is leaked (i.e., where the leak occurs in the cycle) dictates the mass flow rate of the leak. This is an important parameter that influences the dispersion and likelihood of the formation of accumulated fuel volumes or jet plumes.

A gap outside the scope of the present study, but worth mentioning, is the limited amount of data available on leak frequencies for commercial refrigeration equipment. As discussed below in Section 5.4.1, the leak frequencies applied in the risk assessment are derived from a single dataset and therefore the uncertainty is higher than if derived from multiple datasets.

<u>*Consequence Gaps*</u>

The quantitative ignition consequences of leaked R-290 are not well-established. Out of the studies identified in the available literature, only two explored the post-ignition consequences of simulated R-290 leaks. Ref. [3] made visual observations of post-ignition severity, and ref. [5] measured overpressures. Hazards such as thermal radiative exposure direct flame contact exist during post-ignition events, in addition to overpressures, and their severity need to be quantified to fully assess risk. Furthermore, past studies did not consider leaks into closed refrigerated display cases, thus the hazards and their severity for this scenario have not been confirmed or quantified.

The relationship between charge size and consequence has not been fully established either. The available experimental and numerical data show that larger charge sizes can result in larger accumulated fuel volumes, but more data is needed to demonstrate how severity changes with charge size and/or fuel volume size.

2.7 Environmental Settings and Sources of Ignition

The scope of the present project is to evaluate the hazards of A3 refrigerants in commercial retail and kitchen settings. Both commercial retail and commercial kitchen settings can vary in size and layout. Based on our own experience with CFD dispersion modeling, as well as the experimental findings outlined above, the room layout will have some impact on the likelihood of flammable cloud formation; however, the room size will be an important factor, especially in terms of maximum permissible charge size.

The biggest difference between the commercial retail and commercial kitchen environments is the possible ignition sources present. Goetzler et al. [14, 15] comprehensively identified possible ignition sources in residential and commercial settings as part of an ASHRAE funded project to establish input parameters for risk assessments. Table 2.3 provided a subset of the ignition sources identified in refs. [14, 15], along with other sources that we have identified for the specific commercial settings of interest. The table is representative only as there is a myriad of specific cooking appliances that could be considered competent ignition sources.

Table 2.3: List of potential ignition sources identified in commercial retail and kitchen settings.

Electrical Sources	Open Flame Sources
Electric – General wiring	Match
Electric – General capacitors	Butane lighter
Electric - Loose wires	Open fire
Electric - High load electrical switching	Brazing torch
Electric - Damaged electrical components	Pilot light for cooking equipment
Electric - Broken light bulb	Gas oven and stovetop
Electric – Case lighting	Candles
Electric – Thermostats	Wood stoves
Electric – Electrical arc inside the compressor	
Electric – Fluorescent light capacitors	**Hot Surface Sources**
Electric – Cell phone battery discharge	Hot surface igniters (dryers, furnaces)
Electric – Spark igniter	Spark igniters (dryers, grills, water heaters)
Electric – Overloaded extension cord	Griddles
Electric – Unplugged plug and socket	Panini press
Electric – High resistance joint in fuse box	Waffle iron
Component - Condenser fan motor	Portable electric space heaters
Component - Evaporator blower motor	
Component – General electric switches and contacts	**Miscellaneous Sources**
Contactor – Compressor	Spark between fan blade and surface
Contactor – Evaporator motor	Spark between compressor impeller blade and surface
Equipment – Microwave oven	Static charge Build-up
Switch – Manual switch	
Switch – Liquid level switch	
Switch – Flow switch	
Switch – Fan speed controller	
Switch – Pressure switch	
Switch – Programmable controllers	
Switch – Time switches	
Switch – Mini-circuit breakers	
Switch – Fan delay switch	
Switch – Overloading of solid-state components	

Risk assessments for A2L refrigerants typically identify which ignition sources are strong enough to ignite the refrigerant/air mixtures in question, but in this case, propane/air has a very low minimum ignition energy of 0.25 mJ ($5.97x10^{-3}$ cal) and a low auto-ignition temperature of 470 °C (878 °F)[1] and therefore all sources listed above are considered viable. Section 5.4.3 provides further discussion and analysis of ignition probability in commercial kitchen and retail environments.

3 Full-Scale Testing

Gexcon conducted full-scale testing to: (1) Confirm the factors that affect the properties of accumulated fuel volumes and jet plumes; (2) Quantify severity of ignition events for the various fuel volumes and jet fires; (3) Fill research gaps and gaps in the current understanding; (4) Test potential mitigation methods; and (5) Verify FLACS dispersion predictions.

3.1 Design of Experiments

When verifying what factors affect the properties of accumulated fuel volumes, Gexcon had to either limit the range of certain parameters, or fix them at a single condition. When doing so, parameters were fixed or limited to conditions that ensured testing would conservatively quantify event severity. Fixed parameters included low momentum releases (i.e., impinged jets) into a completely sealed room with no room ventilation. With these parameters fixed, other important parameters including charge size, leak rate, leak height, and condenser fan operation could each take on more than one value/condition in the test matrix (e.g., several charge sizes).

To quantify post-ignition event severity, the various accumulated fuel volumes and jet plumes that may form from a leak were created and ignited. Preliminary CFD simulations identified release scenarios and conditions that would yield accumulated fuel volumes and jet plumes with a range of characteristics.

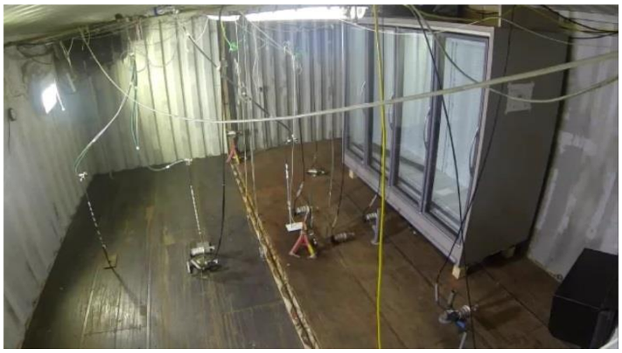
To fill the research gaps previously discussed, higher mass flow rates were considered in comparison to previous studies, corresponding to larger leak sizes and liquid releases. To evaluate risk versus charge size and test mitigation methods, various charge sizes were released and tests were performed with and without a mock-up condenser fan in operation. To enable comparison to CFD predictions, experimental conditions were well-established (e.g., exact leak height and position) so that initial conditions and boundary conditions could be accurately specified in the CFD model.

3.2 Test Room and Display Case

The test room was fabricated from two shipping containers. Gexcon removed one of the walls from each container and joined the two together to create a double-wide container (see Figure 3.1).

[1] National Refrigerants SDS for R-290.

A 2.5 m (8.2 ft) wide, closed refrigerated display case with four doors was provided by panel member and positioned against one of the walls inside the test room (see Figure 3.1).



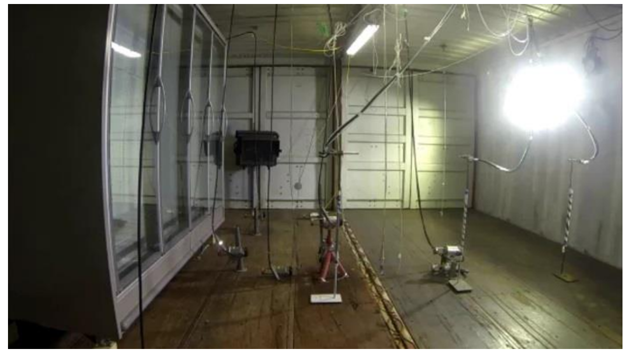


Figure 3.1: Image of the test room taken from the south wall (left) and north wall (right).

Table 3.1 provides the interior dimensions of the test room and the exterior dimensions of the display case. For reference, Table 3.2 gives the resulting % LFL inside the room when different charge sizes are homogeneous mixed in the entire test room volume (charge sizes ranging from 150 g (0.33 lb) to 1000 g (2.2 lb)).

Table 3.1: Dimensions of the test room interior and refrigerated display case exterior.

Dimensions	Test room interior	Cabinet exterior
Length	5.9 m (19.4 ft)	2.5 m (8.2 ft)
Width	4.7 m (15.4 ft)	0.95 m (3.1 ft)
Height	2.4 m (7.9 ft)	2.0 m (6.6 ft)
Floor Area	27.7 m^2 (299 ft^2)	1.9 m^2 (20.5 ft^2)
Volume	66.4 m^3 (2347 ft^3)	4.75 m^3 (168 ft^3)

Table 3.2: For different charge sizes, the % LFL in the test room if the entire charge mixed homogenously in the test room.

R-290 mass	%LFL in test room if homogeneously mixed
150 g (0.33 lbs)	6%
300 g (0.66 lbs)	12%
600 g (1.32 lbs)	24%
1000 g (2.2 lbs)	40%

3.3 Instrumentation and Data Collection

The test room contained 13 gas sensors positioned at the floor and 20 cm, 50 cm, and 100 cm above the floor to measure the concentration of R-290 during dispersion and ignition tests. A pressure transducer measured the pressure rise during post-ignition events. 13 thermocouples measured the temperature rise at different locations in the room. Three heat flux gauges measured the radiative heat flux, and lastly, two high-speed cameras and two standard-speed cameras recorded the flame propagation. Sensor wiring was hung from the ceiling so that cables minimally interfered with the R-290 dispersion along the floor. Figure 3.2 gives the locations of all the instrumentation in the test room, including the ignitors.

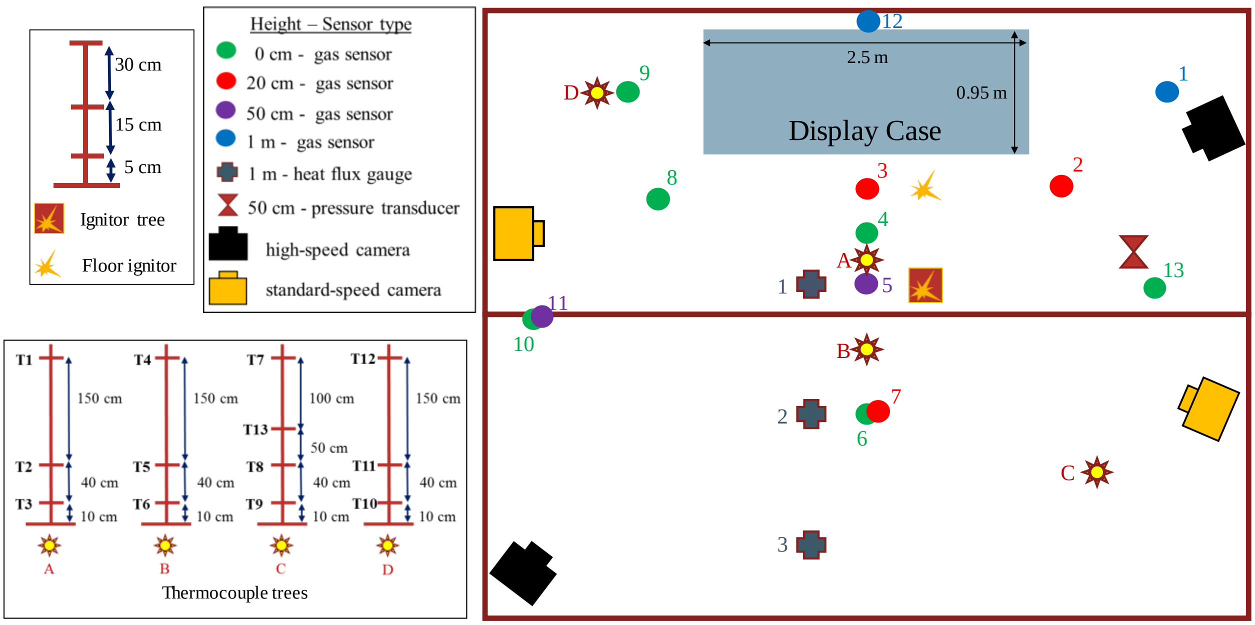


Figure 3.2: Instrumentation and locations in the test room during dispersion and ignition tests. Ignition source locations during ignition tests.

3.4 Dispersion Tests

Dispersion tests were performed to evaluate the outcome of R-290 leaks inside a condensing unit (i.e., outside the closed display case). Table 3.3 provides the different leak parameters and conditions tested for each parameter. All combinations were considered, resulting in a total of 48 tests. Note that charge size and released mass are synonymous as it was assumed the entire charge would be released in the event of a leak.

Table 3.3: Test conditions during leaks from the condensing unit.

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

During dispersion tests, R-290 was released into the test room at constant mass flow rates of 12 g/min, 120 g/min, and 335 g/min. Depressurization within the refrigerant system was not considered to conservatively estimate the highest leak rate for the entire leak duration. The display case remained off during all testing. Leaks did not originate from the closed-loop cycle of the display case, rather ambient temperature vapor R-290 was released from a supply cylinder and the mass flow rate was set using a flow meter. For reference, Table 3.4 provides the leak diameters that would result in the tested mass flow rates assuming a vapor or liquid release from the high-pressure side of the cycle (i.e. the condenser side). As discussed further in Section 5.4.1, leak frequency data indicates that 96% of leaks that are likely to occur will be smaller than the largest leak considered during testing.

Table 3.4: Experimental leak rates and corresponding leak diameters for vapor and liquid leaks on the high-pressure side (i.e., the condenser side).

Leak rate	Leak diameter for vapor @ 55 °C (131 °F) and 18.1 barg (263 psig)	Leak diameter for liquid @ 55 °C (131 °F) and 18.1 barg (263 psig)
12 g/min (0.03 lb/min)	0.22 mm (0.009 in)	0.10 mm (0.004 in)
120 g/min (0.26 lb/min)	0.69 mm (0.027 in)	0.32 mm (0.013 in)
335 g/min (0.74 lb/min)	1.15 mm (0.045 in)	0.54 mm (0.021 in)

Recall that leaks were not created in the closed-loop cycle of the display case, but instead a cylinder outside the test room supplied R-290. A hose from the cylinder delivered R-290 in the vapor phase at either the top or bottom of the display case to represent leaks from top- and bottom-mounted units. During releases with the condenser fan off, the end of the supply hose was placed inside a small box to reduce the leak momentum by forcing the released jet to impact the wall of the box. As shown in Figure 3.3, the box volume and outlet area varied depending on the release mass flow rate so that the velocity of R-290 releases were similar in all tests. Furthermore, the openings in the boxes were positioned downward (opposite as shown in Figure 3.3) to further ensure leak momentum was conservatively low. The release boxes were located 2 m from the floor during top releases and on the floor during bottom releases.

Figure 3.3: R-290 was released inside small boxes varying in size depending on the release mass flow rate to ensure release momentum was conservatively low.

For leak tests with the condenser fan in operation, the R-290 release nozzle was placed in a mock-up condensing unit positioned above or below the display case. A 20.3 cm (8 in) diameter variable-speed fan was mounted in the mock-up condensing unit (see Figure 3.4). For display cases, the condenser fan flow rate is proportional to the amount of heat that needs to be removed from the condenser which is proportional to the cooling capacity of the unit and hence the charge. Therefore, during tests with the fan on, the fan flow rate was scaled to the four charge sizes released during the tests as shown in Table 3.5 [2]. In other words, the cooling capacity and charge size, along with the associated condenser fan flow rate, were not based on the design of the display case inside the test room, but rather four distinct units containing the available charge sizes of 150, 300, 600 and 1000 g (0.33, 0.66, 1.3, 2.2 lb).

Figure 3.4: Mock-up condensing unit, variable-speed fan, and release orifice positioned to cause impingement against the roof of the housing.

Table 3.5: Condenser fan flow rate when releasing different charge sizes.

Charge size	Condenser fan flow rate
150 g (0.33 lbs)	150 m^3/hr (5297 ft^3/hr)
300 g (0.66 lbs)	300 m^3/hr (10594 ft^3/hr)
600 g (1.3 lbs)	600 m^3/hr (21188 ft^3/hr)
1000 g (2.2 lbs)	1000 m^3/hr (35314 ft^3/hr)

Results - Condenser fan off

In general, R-290 concentrations were highest at the floor and decreased with height during releases with the condenser fan off. Accumulated fuel volumes were not observed above a height of 50 cm (1.6 ft) in any test, with the exception of behind the display case when releases occurred at the top.

Figure 3.5 provides measured R-290 concentrations at the different floor sensors for top and bottom leaks of 150 g (0.33 lb) at leak rates of 12 g/min (0.03 lb/min), 120 g/min (0.26 lb/min), and 335 g/min (0.74 lb/min). Note that the numbers in the legends correspond to sensor positions established in Figure 3.2. As shown in the figure, when releasing 150 g (0.33 lb) from the bottom of the display case, R-290 concentrations exceeded LFL at the floor, even when the release rate was 12 g/min (0.03 lb/min) (i.e., the lowest leak rate tested). When releasing 150 g (0.33 lb) from the top of the case, concentrations exceeded LFL at the floor, but only when the release rate was 120 g/min (0.26 lb/min) or 335 g/min (0.74 lb/min). Note the horizontal dotted red lines at 2.1% and 9.5% represent the LFL and UFL of R-290 respectively.

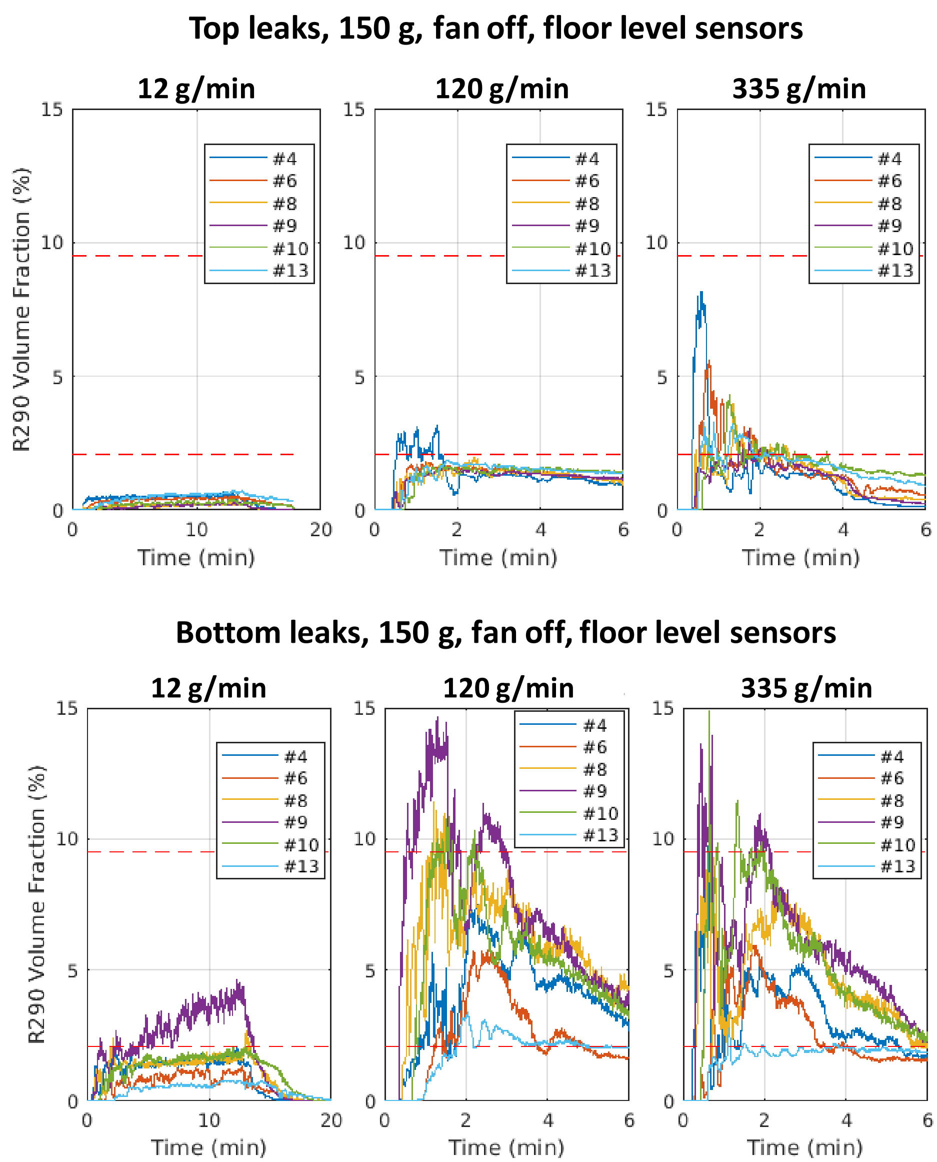


Figure 3.5: R-290 concentrations measured at the floor sensors for bottom (bottom frames) and top (top frames) releases of 150 g (0.33 lb) with the condenser fan off, at leak rates of 12 g/min (0.03 lb/min), 120 g/min (0.26 lb/min), and 335 g/min (0.74 lb/min). Refer to Figure 3.2 for sensor locations based on the numbers provided in the legends.

Higher mass flow rate resulted in higher R-290 concentrations near the floor during both top and bottom releases (see Figure 3.5 and Figure 3.6). During bottom releases, concentrations were likely lower during and at the end of the test with the lowest leak rate of 12 g/min (0.03 lb/min) because there are inevitably some convective currents in the room in addition to the longer leak duration providing more time for R-290 to diffusive mix upward from the layer along the floor.

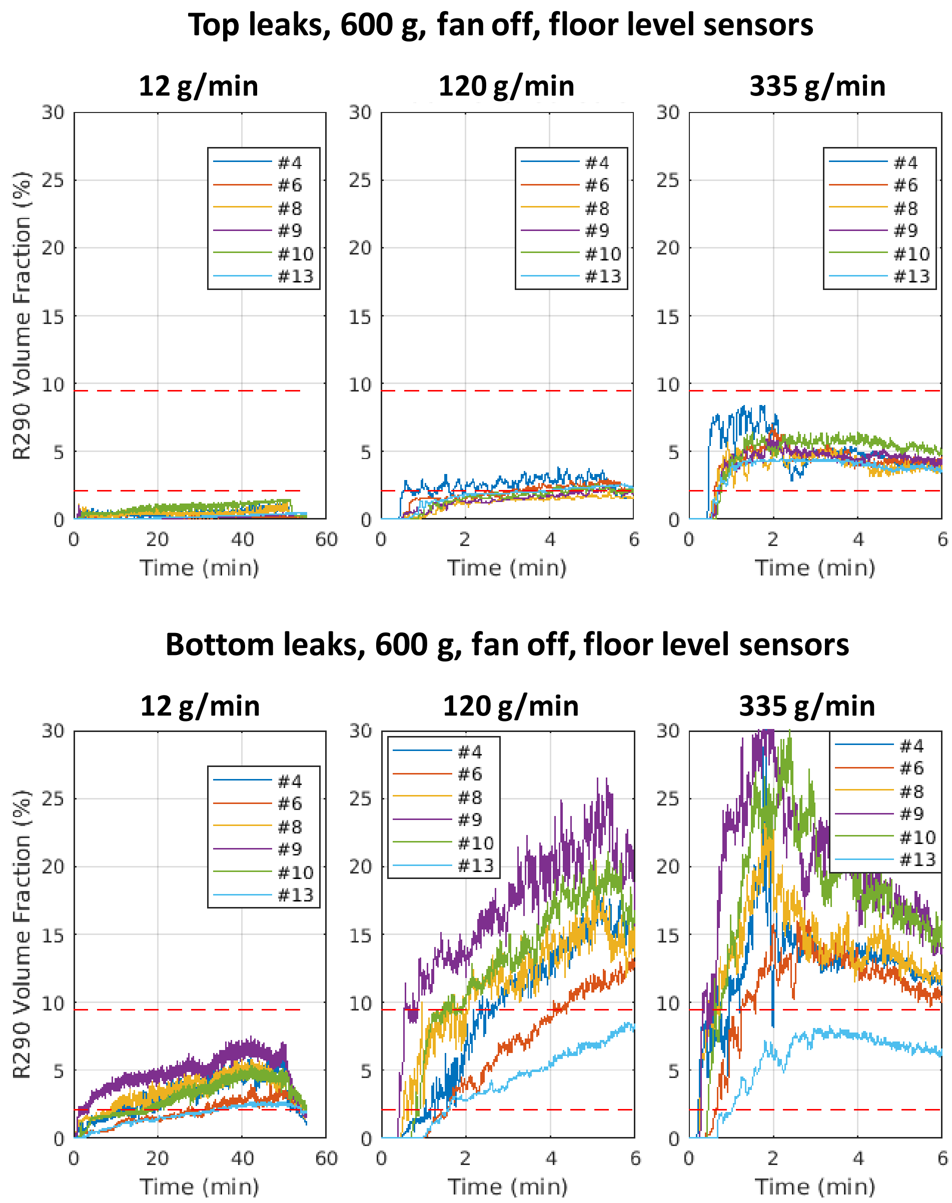


Figure 3.6: R-290 concentrations measured at the floor sensors for bottom (bottom frames) and top (top frames) releases of 600 g (1.32 lb) with the condenser fan off, at leak rates of 12 g/min (0.03 lb/min), 120 g/min (0.26 lb/min), and 335 g/min (0.74 lb/min). Refer to Figure 3.2 for sensor locations based on the numbers provided in the legends.

Mass flow rates of 120 g/min (0.26 lb/min) or higher from the top always caused R-290 concentrations to exceed the LFL at the floor. This is a significant result that was not observed in previous studies because testing was done with leak rates of 60 g/min (0.13 lb/min) or lower [1, 7, 9]. While larger leaks are less likely, they need to be accounted for when assessing risk as they can result in different outcomes compared to the smaller, more likely leaks.

Top and bottom releases can create layers at the floor with different characteristics. Figure 3.7 shows the concentrations at the floor and at 20 cm (0.66 ft) and 50 cm (1.64 ft) above the floor during the bottom (left frames) and top (right frames) release of 1000 g (2.2 lb). The bottom release created a thin rich layer at the floor, whereas the top release created a taller layer with R-290 concentrations within the flammability limits.

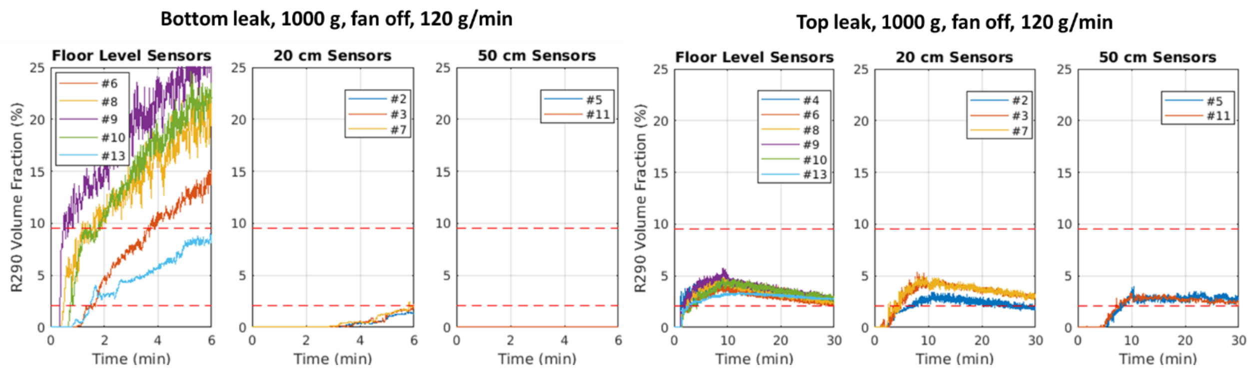


Figure 3.7: R-290 concentrations measured at the floor and at 20 cm (0.66 ft) and 50 cm (1.64 ft) above the floor during a bottom (left) and top (right) release of 1000 g (2.2 lb), with the condenser fan off, and with a leak rate of 120 g/min (0.26 lb/min). Refer to Figure 3.2 for sensor locations based on the numbers provided in the legends.

The main findings from the dispersion tests with the condenser fan off are summarized below:

1) Low momentum releases created accumulated fuel layers near the floor.
2) R-290 concentrations were the highest at the floor and decreased with height.
3) Accumulated fuel volumes were not observed above a height of 50 cm (1.64 ft), except for behind the display case during top releases.
4) Concentrations at the floor increased with leak rate.
5) Low momentum releases of 150 g (0.33 lb) resulted in accumulated fuel volumes near the floor, even for 12 g/min (0.03 lb/min) releases at the bottom of the display case.
6) Releases at the top of the display case resulted in accumulated fuel volumes when the leak rate was 120 g/min (0.26 lb/min) or higher.
7) Top and bottom releases formed accumulated fuel layers with different characteristics
    a. Top releases resulted in a taller layer with flammable R-290 concentrations extending up to a height of 50 cm (1.64 ft).
    b. Bottom releases resulted in much higher concentrations well above the UFL at the floor and minimal concentrations at a height of 50 cm (1.64 ft).

Results - Condenser fan on

Condenser fan operation significantly reduced peak R-290 concentrations in the test room and resulted in more uniform mixing. Examples are provided in Figure 3.8, which compares R-290 concentrations with the fan off (left frames) and on (right frames) during bottom the release of 600 g (1.32 lb) at 12 g/min (0.03 lb/min). Figure 3.9 provides the same comparison during the top release of 600 g (1.32 lb) at 335 g/min (0.74 lb/min).

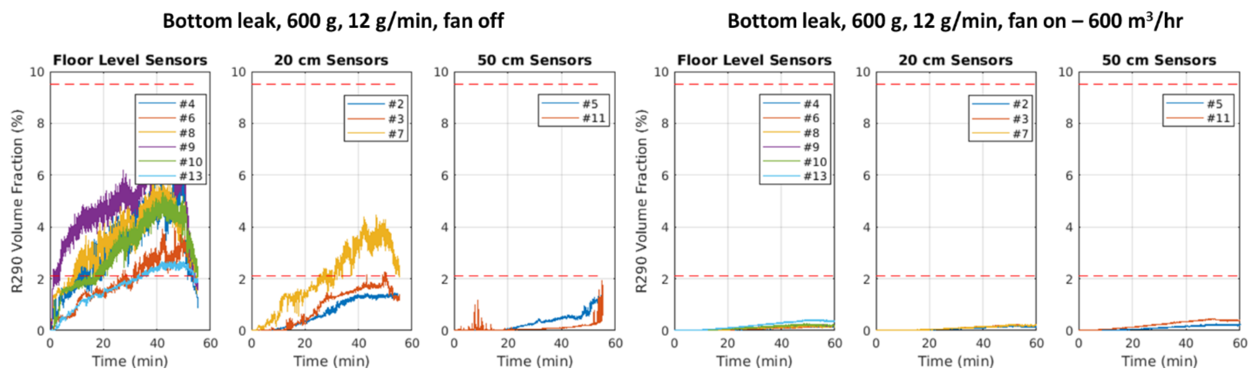


Figure 3.8: R-290 concentrations measured at the floor and at 20 cm (0.66 ft) and 50 cm (1.64 ft) above the floor during a bottom release of 600 g (1.32 lb) at 12 g/min (0.03 lb/min) with the condenser fan off (left) and on (right). Refer to Figure 3.2 for sensor locations based on the numbers provided in the legends.

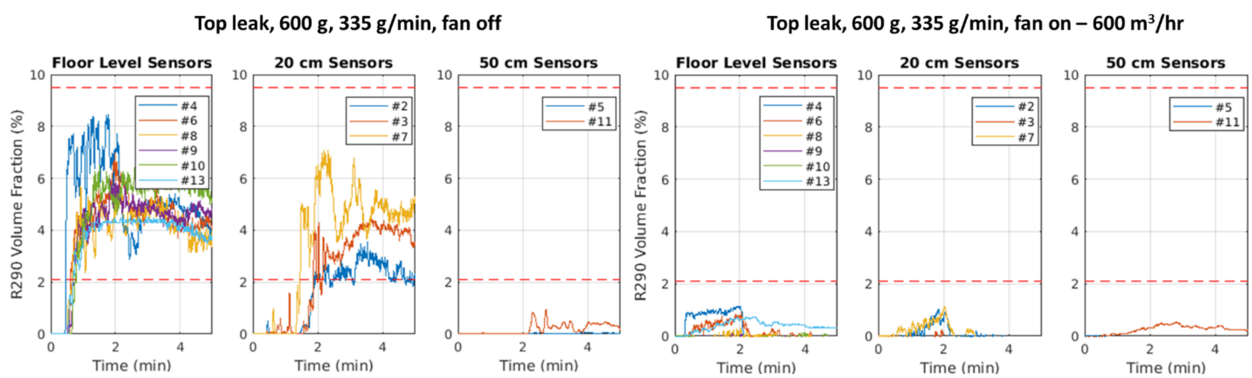


Figure 3.9: R-290 concentrations measured at the floor and at 20 cm (0.66 ft) and 50 cm (1.64 ft) above the floor during a top release of 600 g (1.32 lb) at 335 g/min (0.74 lb/min) with the condenser fan off (left) and on (right). Refer to Figure 3.2 for sensor locations based on the numbers provided in the legends.

As the leak rate increases, higher fan flow rates are needed to maintain dilution and prevent fuel volumes from accumulating at the floor (see Figure 3.10). R-290 concentrations remained below the LFL in all tests with the fan on except for the top and bottom release of 150 g (0.33 lb) at the highest leak rate of 335 g/min (0.74 lb/min). These tests had the lowest fan flow rate of 150 m^3/hr (5297 ft^3/hr) (scaled to charge size), and thus not enough mixing and dilution occurred during the 335 g/min (0.74 lb/min) release to prevent R-290 concentrations from exceeding the LFL at floor.

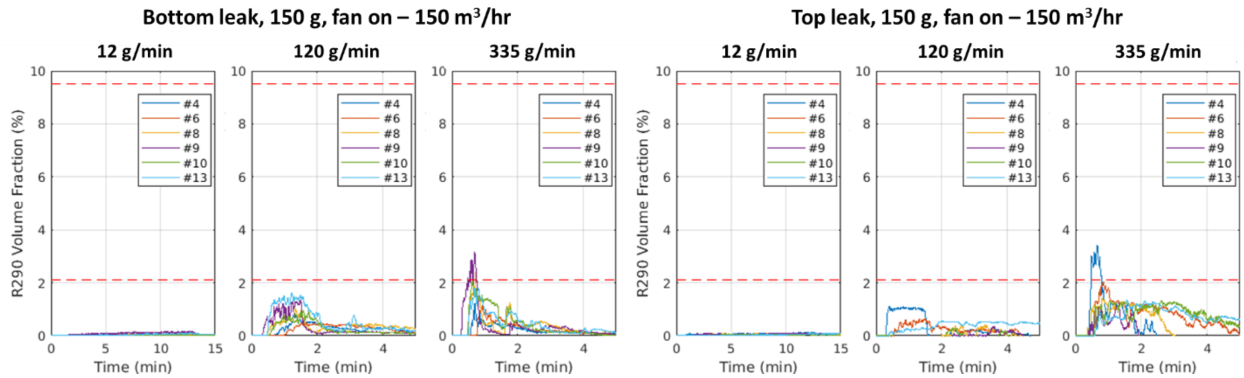


Figure 3.10: R-290 concentrations measured at the floor sensors for bottom (left) and top (right) releases of 150 g (0.33 lb) with the condenser fan on, at a release rate 12 g/min (0.03 lb/min), 120 g/min (0.26 lb/min), and 335 g/min (0.74 lb/min). Refer to Figure 3.2 for sensor locations based on the numbers provided in the legends.

Figure 3.11 demonstrates that higher fan flow rates can prevent concentrations from exceeding LFL at the floor during both bottom and top releases of 335 g/min (0.74 lb/min). At a fan flow rate of 300 m^3/hr (10594 ft^3/hr), sufficient mixing takes place and R-290 concentrations are diluted below the LFL.

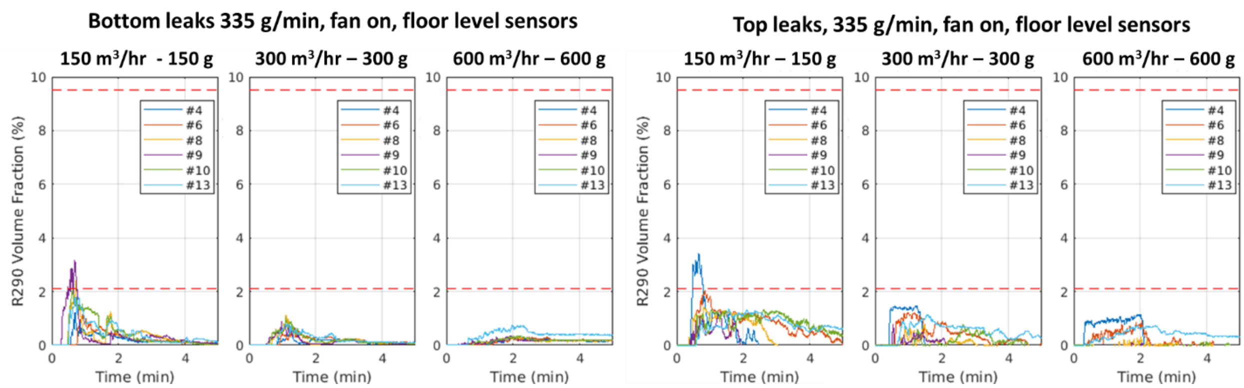


Figure 3.11: R-290 concentrations measured at the floor sensors for bottom (left) and top (right) releases of different charge amounts at 335 g/min (0.74 lb/min) with the condenser fan on at a flow rate of 150 m^3/hr (5297 ft^3/hr), 300 m^3/hr (10594 ft^3/hr), and 600 m^3/hr (21188 ft^3/hr). Charge amount is scaled to fan flow rate. Refer to Figure 3.2 for sensor locations based on the numbers provided in the legends.

The main findings from the dispersion tests with the condenser fan on are summarized below:

1) Condenser fan operation significantly reduced peak R-290 concentrations in the test room and resulted in the dilution of R-290 concentrations below LFL.
2) As the leak rate increases, higher condenser fan flow rates are needed to maintain dilution and prevent fuel volumes from accumulating.

3.5 Ignition Tests

Gexcon ignited: (1) R-290 releases outside the display case; (2) R-290/air mixtures exiting the display case after an internal leak; and (3) vapor and liquid jet flames external to the display case. During each test, cameras filmed the post-ignition event and sensors measured temperature, pressure, and thermal flux.

Twelve of the dispersion tests (leaks from the mock-up condensing unit) were repeated with ignition sources inside the test room. Sensors measured the concentration of R-290 up to the point of ignition, and for all tests, concentrations were similar to those observed during the dispersion tests. Ignition sources were activated at the end of the leak. High-voltage AC transformers created continuous sparks at the two lowest ignition locations and hot-wires were positioned at the two upper ignition locations (ignition locations shown in Figure 3.2).

Gexcon performed two additional tests with 900 g (1.98 lb) charges leaked inside the closed display case. Since the concentration of R-290 within the display case after a leak depends on the internal volume, the actual charge size of 900 g (1.98 lb) for the exemplar display case was released in both tests. In one test, R-290 was released into the display case as a free jet so that the contents inside the display case would mix uniformly. Due to the intimate mixing of the R-290 and air from the jet, this scenario also represents a leak in the display case while the evaporator fan is on and mixes the released fuel. In the second test, R-290 was released with low momentum to create a smaller, yet higher average concentration of R-290, accumulated fuel volume inside the display case. Once the leaks ended, a door on the unit was opened, allowing the fuel volume to exit into the room. For these tests, ignition sources were also placed outside the display case in the locations shown in Figure 3.2.

In the last two tests, free jet releases of R-290 were ignited to create jet fires. A charge size of 1000 g (2.20 lb) of both vapor and liquid were released through a 2 mm (0.08 in) diameter orifice located in front of the display case at a height of 1 m (3.3 ft). The position was not chosen to be representative of a likely release location, but so that the flame length could be easily filmed and the heat flux could be measured with only minor changes to the sensor positions. During these tests, the sensors were positioned axially along the floor, 0.61 m (2 ft), 1.22 m (4 ft), and 1.83 m (6 ft) from the release orifice, and with the sensor elements facing upward. Pressure and temperature sensors were not active for these two tests. The mass flow rate was not controlled with a mass flow meter like in the previous tests, but instead dictated by the size of the orifice (2 mm (0.08 in) diameter) and the delivery pressure of R-290 (vapor pressure at 17.2 °C (63 °F)). The estimated mass flow rate was 380 g/min (0.84 lb/min) and 3050 g/min (6.72 lb/min) during the vapor and liquid release, respectively. An ignitor was placed downstream of the release orifice to initiate a jet flame.

Table 3.6 provides the conditions for each test along with the main results. The table includes release location, leak mass flow rate, whether the condenser fan was active, released charge size, whether ignition was observed, maximum pressure rise, maximum temperature recorded at any thermocouple, and peak heat flux measured by the three sensors (all measurement device positions are provided in Figure 3.2).

Table 3.6: Conditions and main results of each ignition test.

Ingition test #	Release location	Leak rate (g/min)	Ventilation (off/on)	Charge size (g)	Δp_{max} (psig)	T_{max} (°F)	Peak heat flux (kW/m²)		
							Sensor #1	Sensor #2	Sensor #3
1	Bottom	12	Off	150		840	13	3.0	1.4
2	Bottom	12	Off	600	0.95	1400	82	41	28
3	Bottom	120	Off	150	0.15	950	19	13	7.1
4	Bottom	120	Off	300	0.8	820	38	30	13
5	Bottom	120	Off	600	0.9	1500	97	63	23
6	Bottom	120	Off	1000	0.2	1000	-	-	-
7	Bottom	120	On	600	-	-	-	-	-
8	Top	12	Off	600	-	-	-	-	-
9	Top	120	Off	150	0.35	850	24	7.0	4.4
10	Top	120	Off	300	0.5	720	19	13	13
11	Top	120	Off	600	0.67	1100	110	72	84
12	Top	120	Off	1000	1.11	1620	120	120	93
13	Inside	120	Off	900	0.59	1450	90	58	28
14	Inside	240	Off	900	0.86	1472	120	91	34
15	Vapor Jet	380	Off	1000	-	-	0.62	0.36	0.16
16	Liquid Jet	3050	Off	1000	-	-	5.6	6.8	6.0

Ignition occurred in all tests except for #7 and #8. During test #6, R-290 migrated under the floorboards and the high-speed video clearly showed a confined deflagration below the floorboards that damaged the floor and contributed to the severity of the event. The confined deflagration below the floorboards also knocked out the data acquisition equipment for the sensors, hence the lack of data presented in the table. After test #6, the floor was repaired and all floorboard seams were covered with heat resistant tape to prevent R-290 from migrating below again.

Ignition occurred in test #5 when 600 g (1.32 lb) were released at 120 g/min (0.26 lb/min) from the bottom of the unit. Test #7 was a repeat of test #5, but with the condenser fan on. Ignition did not occur during this test confirming that the fan operation prevents concentrations from exceeding LFL along the floor and results in more homogeneous mixing.

Figure 3.12 provides snapshots from tests #3 and #5 with 150 g (0.33 lb) and 600 g (1.32 lb) charges released at 120 g/min (0.26 lb/min) from the bottom of the unit while the condenser fan was off. The left image shows the flames shortly after ignition, the center image shows the flames at their most intense state, and the right image shows the flames just prior to extinction. As seen in the figure, ignition after leaking larger charge sizes resulted in more intense flames that were taller and extended throughout a large portion of the test room. Note that the enclosure door was left open in test #3 and sealed with a 4 mil plastic sheet which did not yield during the ignition event. Therefore, the comparison of test #3 in Figure 3.12 (and in Figure 3.14) to a test with the door closed is valid.

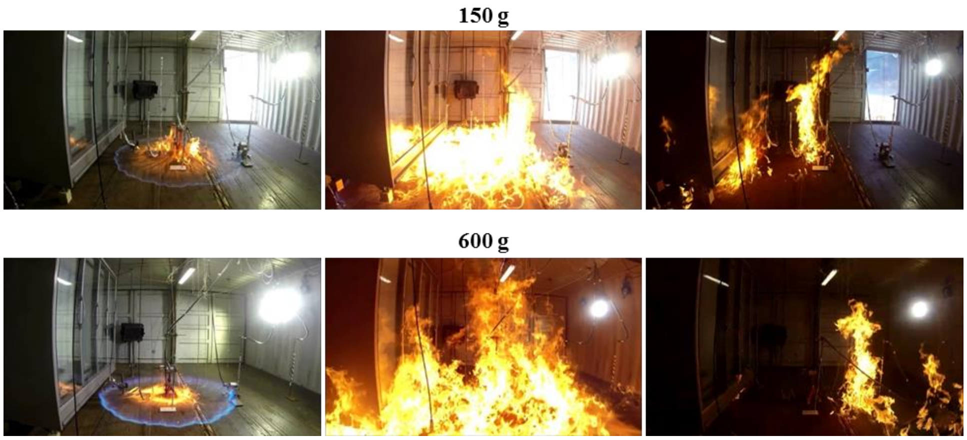


Figure 3.12: Test #3 (top images) and #5 (bottom images), bottom releases, 120 g/min (0.26 lb/min), condenser fan off.

The images in Figure 3.13 compare tests #10 and #12 with 300 g (0.66 lb) and 1000 g (2.2 lb) charges released at 120 g/min (0.26 lb/min) from the top of the unit while the condenser fan was off. As observed during the bottom-release tests, flames extended further from the ignition source, both horizontally and vertically, as the released charge size increased.

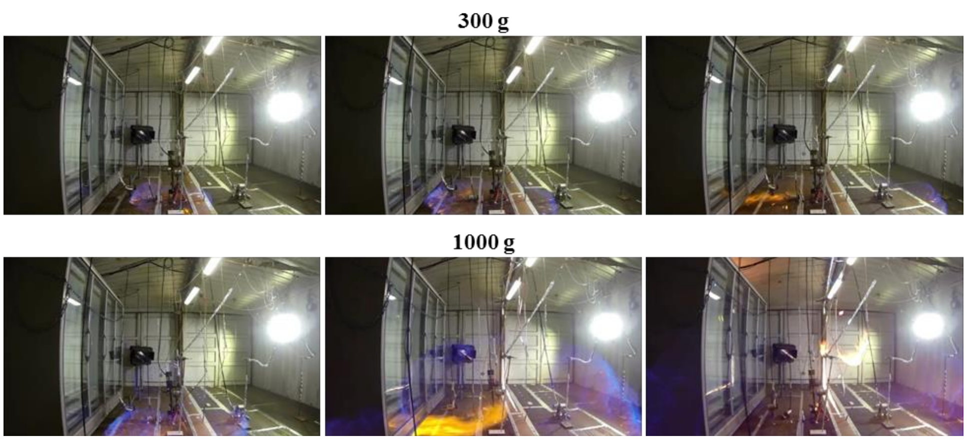


Figure 3.13: Tests #10 (top images) and #12 (bottom images), top releases, 120 g/min (0.26 lb/min), condenser fan off.

When released at the bottom of the display case, ignition events occurred for the 12 g/min (0.03 lb/min) releases, however these events were less intense than the events occurring for the 120 g/min (0.26 lb/min) releases. This is demonstrated in Figure 3.14 where 150 g (0.33 lb) was released and in Figure 3.15 where 600 g (1.32 lb) was released.

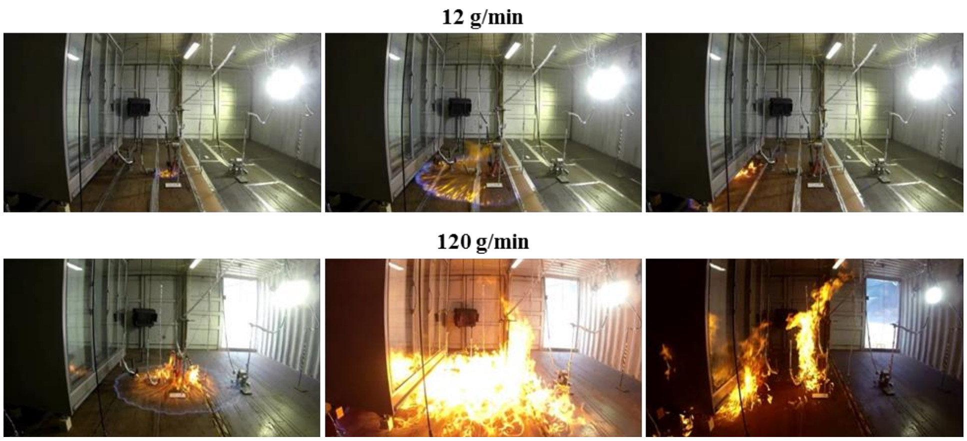


Figure 3.14: Test #1 (top images) and #3 (bottom images), bottom release, 150 g (0.33 lb), condenser fan off.

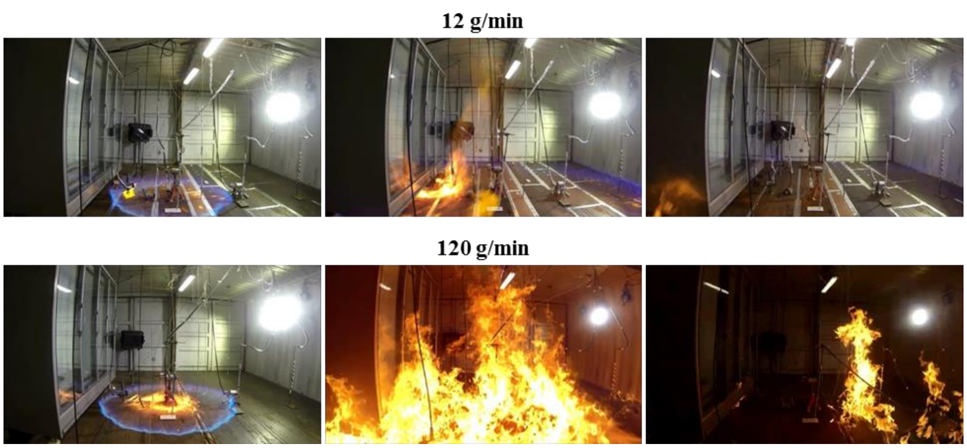


Figure 3.15: Test #2 (top images) and #5 (bottom images), bottom release, 600 g (1.32 lb), condenser fan off.

In the ignition tests, event severity increased with the release mass flow rate. For example, the 12 g/min (0.03 lb/min) release of 600 g (1.32 lb) from the top of the display case (test #8) did not result in ignition. When leaked at 12 g/min (0.03 lb/min), the leaked R-290 was able to sufficiently mix as it migrated toward the floor such that concentrations remained below the LFL. Conversely, the 120 g/min (0.26 lb/min) release of the same charge amount and at the same location (test #11) resulted in intense flames almost throughout the entire test room.

As illustrated in Figure 3.16, the combustion events were different when igniting releases from the top and bottom of the display case. Top leaks created a taller layer within the flammability limits, resulting in more of a premixed flame propagation upon ignition. Bottom leaks created thin rich layers above the UFL at the floor resulting in large diffusion flames more typical of pool fires. As noted above, in test #6 (see the top images of Figure 3.16), R-290 migrated under the floorboards and the high-speed video clearly showed a confined deflagration originating under the floor that damaged the floor and contributed to the severity of the event.

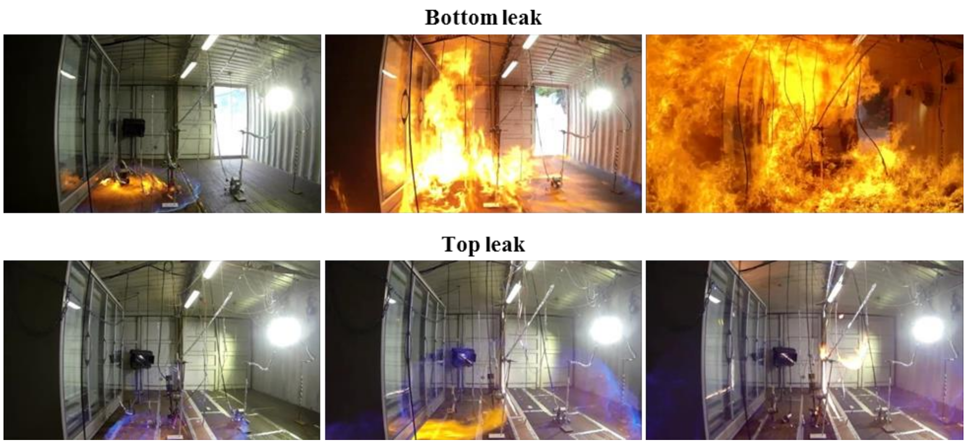


Figure 3.16: Test #6 (top images) and #12 (bottom images), 1000 g (2.2 lb), 120 g/min (0.26 lb/min), condenser fan off.

Figure 3.17 provides snapshots of the tests with releases inside the display case. After the releases ended, one of the display case doors was opened with a pull-string extending through the opposite wall of the test room. In both tests, ignition occurred in front of the display case 3-5 seconds after the door was opened. The size and intensity of the flames looked similar to when 600 g (1.32 lb) and 1000 g (2.2 lb) were released at the bottom of the display case, however the flame durations were longer.

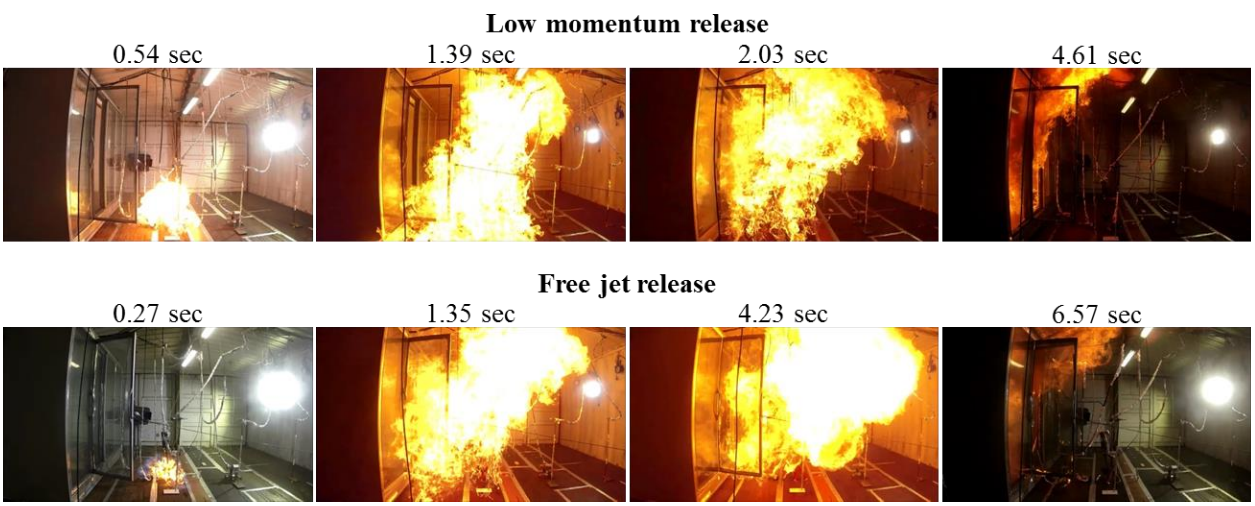


Figure 3.17: Ignition events for low momentum (top images) and free jet (bottom images) releases inside the display case.

Figure 3.18 provides the measured peak pressure rise when igniting leaks outside and inside the display case. Pressure rise ranged from 0.01 barg (0.15 psig) to 0.077 barg (1.11 psig) and generally increased with charge size, but was also influenced by venting paths in the room. In several tests, the initial pressure rise deformed the walls and ceiling creating a venting path at the junction of the two containers (see Figure 3.19). To prevent further deformation and potential damage to the test room, the enclosure door was left open and sealed with a 4 mil plastic sheet to provide additional venting during test #6 with a bottom release 1000 g (2.2 lb), and thus the data for this test is represented in the figure with an asterisk. While the door was also left open for test #3, the plastic sheet did not yield and therefore there is no distinction between this point and the rest of the data. In general, due to the venting at the ceiling, the peak pressures observed in these tests are lower than what would occur in a completely enclosed room with no venting paths, and this is especially true for test #6 because of the additional venting through the open door.

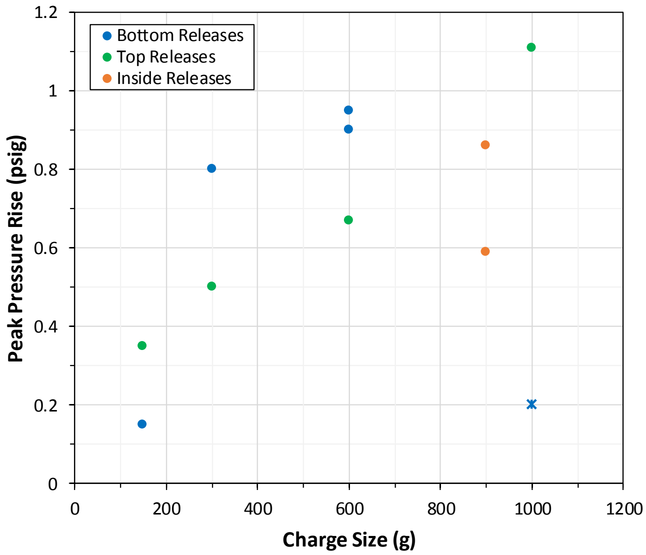


Figure 3.18: Peak pressure rise for ignition of releases above, below, and inside the display case. Note that the door to the test room was left open for additional venting during the test with a bottom release of 1000 g (2.2 lb) and therefore the data is shown with a different symbol in the figure.

Figure 3.19: Ignition events deformed the roof of the test room and created a venting path.

There are limited data that describe the relationship between the magnitude of overpressures occurring in rooms or buildings and the damage it causes to structures. While it is difficult to provide generic data on explosion damage since the failure of walls, doors, and windows are dependent on the construction, it is expected that many of these elements will fail at pressures below 1 psig. The ensuing damage or injuries caused by the venting gases via the failed structural elements were considered outside the scope of the present study.

Thermal flux was measured at three locations inside the test room (see Figure 3.2 for locations). As shown in Figure 3.20, the peak thermal flux (measured at any of the three sensor locations) increased with charge size and was generally insensitive to whether R-290 was released at the top, bottom, or inside the display case. Thermal heat flux was not recorded during test #6 (bottom release, 1000 g (2.20 lb), 120 g/min (0.26 lb/min), condenser fan off) because the data acquisition system was affected by the confined deflagration that originated under the floorboards. Note that the measurement accuracy was ± 3% of reading for peak thermal fluxes up to 90 kW/m^2 (28.5 Btu/hr-ft^2) due to the measurement range of the sensors, and that measurements above 90 kW/m^2 (28.5 Btu/hr-ft^2) had a higher uncertainty.

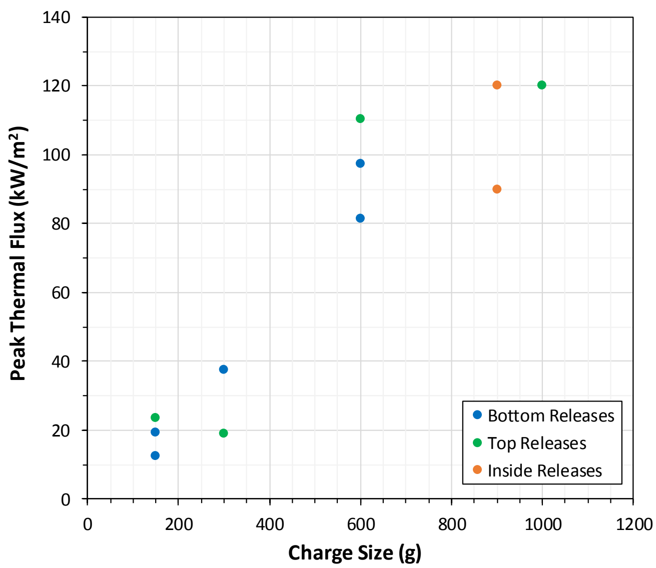


Figure 3.20: Peak thermal flux measured at the three sensor locations for ignition of releases above, below, and inside the display case.

The results are somewhat surprising based on the different flame types observed when igniting top and bottom releases. Typically, premixed flames radiate less than diffusion flames which have higher soot content. However, the peak thermal fluxes correlated generally well with the peak temperatures measured at the thermocouple closest to the sensor where the peak was recorded.

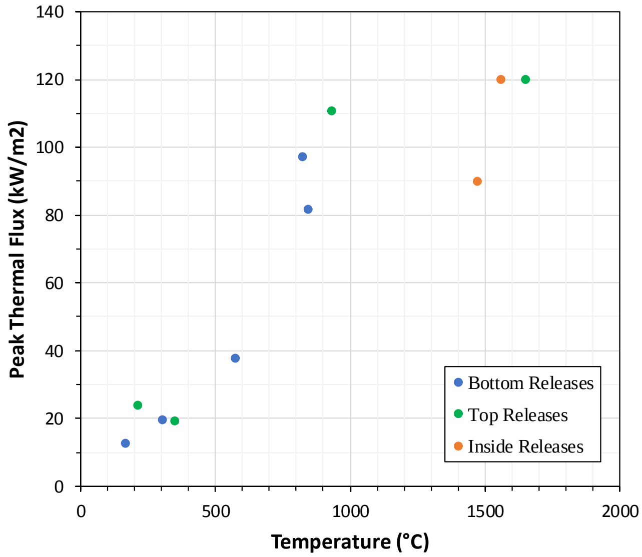


Figure 3.21: Peak thermal flux as a function of peak temperature at the thermocouple closest to the heat flux gauge recording the peak.

The flame duration during each test was determined from the video footage and is plotted in Figure 3.22 versus charge size. As the figure shows, flame durations from top and bottom releases varied from 1-3 seconds and were largely independent of charge size. Leaks inside the display case resulted in longer flame durations.

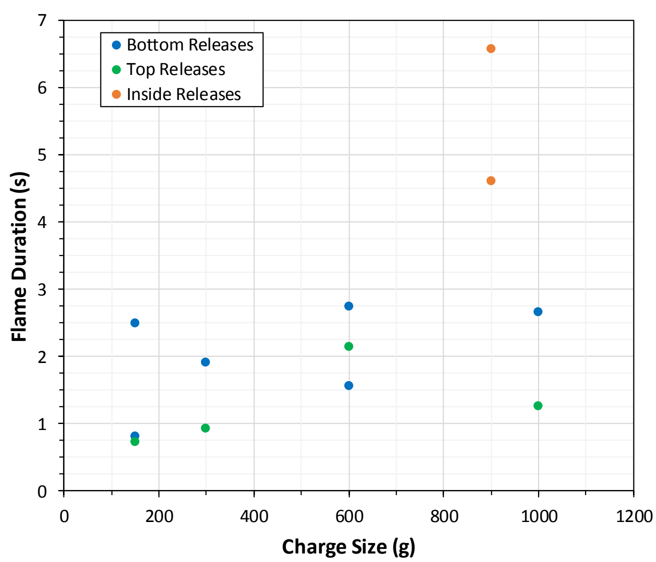


Figure 3.22: Flame duration as a function of charge size for ignition of releases above, below, and inside the display case.

Thermal dose is commonly used to quantify event severity in terms of human vulnerability and can be determined from the experimental data of each test (Eq. 1) [16]:

$$TDU = I^{4/3} * t \qquad \text{(Eq. 1)}$$

where *TDU* is the thermal dose ($(kW/m^2)^{4/3}*s$) or equivalent units of (TDU), *I* is the incident thermal flux (kW/m^2), and *t* is the exposure time. Figure 3.23 provides the maximum thermal flux (at any of the three sensor locations) as a function of charge size. For releases outside the display case, thermal dose trended similarly to heat flux because the flame durations are all similar. Releases inside the display case resulted in somewhat higher thermal doses because the flame durations are longer.

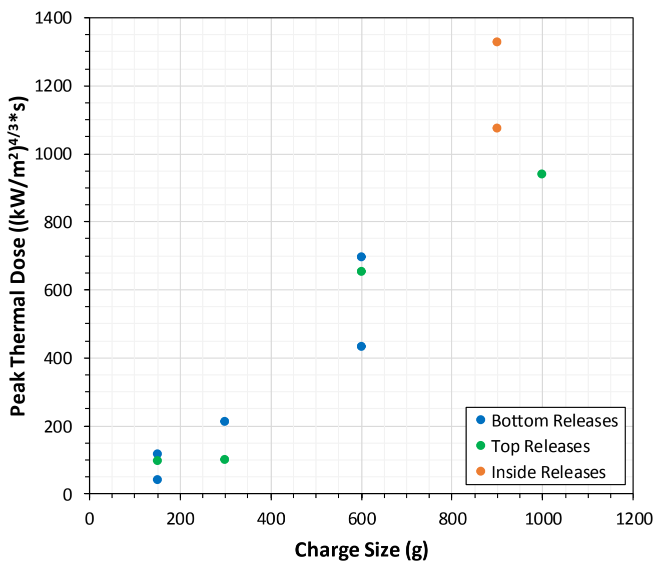


Figure 3.23: Peak thermal dose at the three sensor locations for ignition of releases above, below, and inside the display case.

For the specific test room, the post-ignition events result in peak thermal doses that are a more severe hazard to humans than the overpressures. Table 3.7 provides the approximate effects of thermal dose (from infrared radiation) on the human body. The 150 g (0.33 lb) and 300 g (0.66 lb) releases resulted in thermal doses capable of causing first degree burns. Releases of 600 g (0.66 lb) or more resulted in much more severe thermal doses capable of causing third degree burns and having a 50% lethality level assuming the occupant is wearing average clothing.

Table 3.7: Thermal dose versus human impact from UK HSE [16].

Effect	Thermal Dose $(kW/m^2)^{4/3}*s$ Infrared	Reference
Significant injury level / first degree burns	c.80	Mehta et al (1973)
	130	Tsao & Perry (1979)
Second degree burns / 1% lethality level for average clothing	240	Stoll & Green (1958)
	270-310	Stoll & Green (1958)
	c.350	Mehta et al (1973)
	290-540	Williams et al (1973)
	730	Arnold et al (1973)
Thrid degree burns / 50% lethality level for average clothing	c.500	Mehta et al (1973)

As established in Section 2.4, the only hazard of a free jet release outside the display case is a jet flame if charge sizes are limited to prevent homogeneous environments above LFL. Therefore, Gexcon created vapor and liquid free jet releases of R-290 through a 2 mm (0.08 in) diameter orifice and ignited them with a butane torch to examine the consequences. Close-up and wide-angle images of the jet flames are shown in Figure 3.24 (vapor release) and Figure 3.25 (liquid release). Recall that the position of the release was not chosen to be representative of a likely release location, but instead chosen to easily visualize and quantify the severity of the jet flames. Based on the ambient temperature on the day of the tests (17.2 °C (63 °F)), and the equations for choked and incompressible flow (see Section 2.5), the mass flow rates of the vapor and liquid releases through the 2 mm (0.08 in) diameter orifice were estimated to be 380 g/min (0.84 lb/min) and 3050 g/min (6.72 lb/min) respectively.

As seen in the figures, the resulting jet flame from the vapor release is much smaller and less intense visually than the jet flame from the liquid release. In addition to being much smaller, the vapor jet flame would not stay lit (i.e., would blow off) after removing the ignition source, and thus to get video footage and thermal flux measurements, the butane torch had to be fixed next to the orifice and left on during the entire test. The vapor jet flame extended about 0.6 m (2 ft) from the orifice and created a constant thermal flux around 0.1-0.2 kW/m^2 (0.03-0.06 $Btu/hr\text{-}ft^2$) at the floor sensors. The liquid jet flame extended about 2.4 m (8 ft) from the orifice and created a constant thermal flux around 6-7 kW/m^2 (1.9-2.2 $Btu/hr\text{-}ft^2$) at the floor sensors. Although a 1000 g (2.2 lb) release would last for 158 s and 20 s for the vapor and liquid releases respectively, it is expected that anyone in the vicinity of the display case would quickly move away if a jet flame initiated and would therefore only be exposed to the thermal flux for a few seconds, resulting in thermal dose of about 3 TDU and 40 TDU from the vapor and liquid jet flame, respectively. This assumption however breaks down if someone were to be caught in the actual flame, which was not considered in the present study.

Figure 3.24: Jet flame of a vapor release through a 2 mm (0.08 in) diameter orifice.

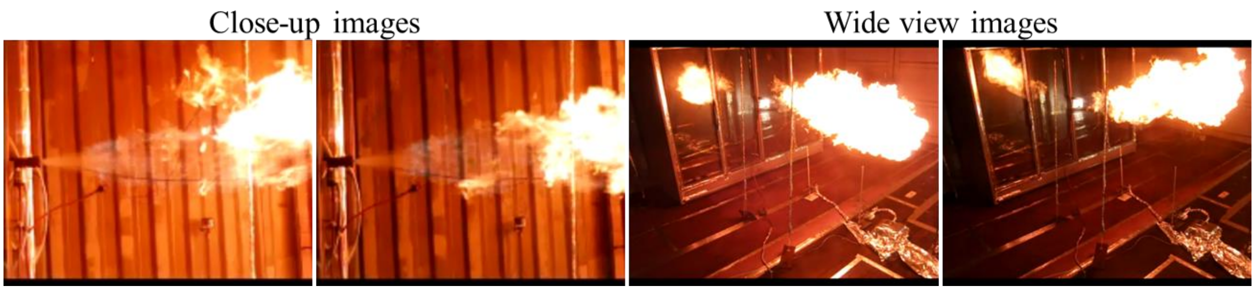


Figure 3.25: Jet flame of a liquid release through a 2 mm (0.08 in) diameter orifice.

The main findings from the ignition tests are summarized below:

1) Post-ignition event severity increased with charge size and mass flow rate.
    a. Increased flame intensity observed in videos
    b. Increased pressure rise
    c. Increased thermal dose
2) Condenser fan operation prevented ignition.
3) Different flame structures were observed when igniting top and bottom releases.
4) Releases inside the display case resulted in similar post-ignition events as releases outside the display case with similar charge sizes.
5) When leaked through the same diameter orifice, the liquid release created a significantly bigger jet flame compared to the vapor release.

4 Comparison of CFD Dispersion Predictions to Measurements

One method of assessing risk, which is adopted in the present study and discussed further below, is to incorporate advanced CFD to predict the dispersion process for different leak scenarios. CFD models such as FLACS have been extensively validated for predicting dispersion processes in many applications. Furthermore, the room-scale dispersion tests offer an excellent means of additionally confirming the suitability of FLACS for predicting the dispersion of R-290 from leaks in refrigerated display cases.

To enable comparison, the dispersion tests discussed in Section 3.4 were simulated in FLACS and the predicted R-290 concentrations were compared to measurements. Comparisons were warranted because outputs from several hundred FLACS dispersion simulations are used as inputs to the risk model developed and implemented in the next section. As stated above, by examining the accuracy of dispersion predictions, we can gauge the accuracy and uncertainty of the inputs to the risk model.

All of the experimental leaks were modeled in FLACS as low-momentum "JET" area leaks with the corresponding release mass flow rate specified directly. The leak profile across the defined area was a uniform profile in an elliptic shape. The domain was resolved based on the leak rate in each test. For the simulations with release rates of 12 g/min (0.03 lb/min) and 120 g/min (0.26 lb/min), the grid cell resolution across the leak was between 1 cm (0.4 in) and 2 cm (0.8 in), with the cell size maintained at 5 cm (2 in) in the area of the sensor and then stretched out to a maximum cell size of 10 cm (3.9 in) beyond the sensors to the walls. For the largest release rate of 335 g/min (0.74 lb/min), the base grid cell size was about 2 cm (0.8 in) with similar cell stretching applied.

R-290 concentration monitor points were placed at the same locations as the gas sensors in the tests. Figure 4.1 shows the FLACS geometry model replicating the test room and display case.

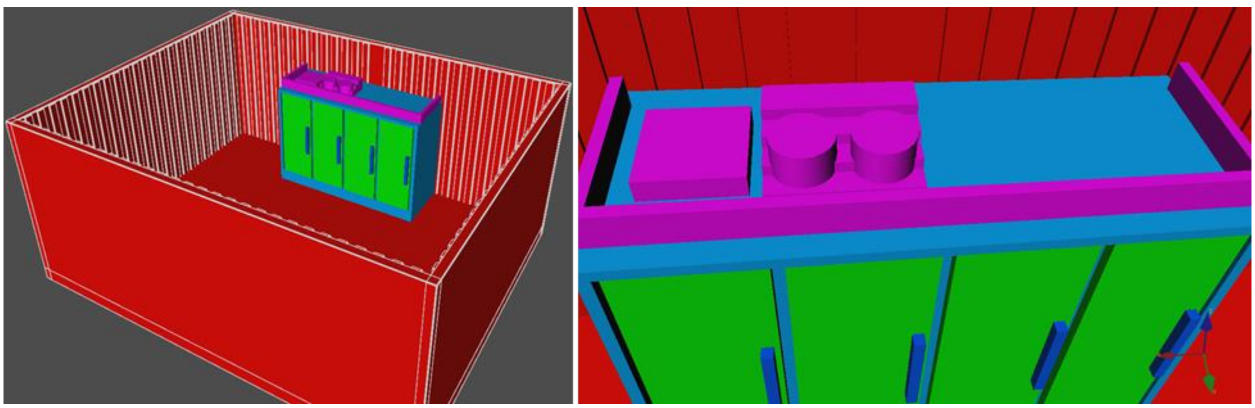


Figure 4.1: FLACS geometry model of the test room and display case. The roof is removed from the test room so that the interior can be viewed.

Below are the main observations when comparing predicted concentrations to measurements:

1. Predicted transient and peak concentrations were in excellent agreement with measurements. On occasion, predicted concentration at a particular sensor was high or low by a few percent, but good overall agreement was typically observed across the majority of sensors at a particular height.
2. In general, FLACS was able to accurately predict the dispersion process for all leak conditions considered and prediction accuracy was equally as good for:
    a. Low and high release heights
    b. Low and high release mass flow rates
    c. Small and large released amounts
    d. Whether the condenser fan was off or on

Provided in Appendix A are comparisons between FLACS predictions and measurements that support the above observations and demonstrate the agreement between the two for the wide range of leak conditions considered during testing. Overall, the results confirm that FLACS is suitable for predicting R-290 dispersion and that using FLACS outputs as inputs in the risk model is a valid approach.

5 Risk Assessment

The quantitative assessment of risk combines much of the information in the previous sections (full-scale experiments, CFD simulations) with additional CFD simulations and a risk-based approach to understand how various aspects of the use of refrigerated cabinets interact to evaluate flammable hazards.

At its simplest, risk is the combination of likelihood of an event occurring and the consequence of the event. For the application of interest, the consequence of an ignited event is directly related to how the refrigerant disperses into a given space, or more specifically, how it mixes with air and accumulates in the space where it is leaked. This aspect dictates the characteristics of the accumulated fuel volumes that forms. The focus of the assessment was to examine larger charge sizes and some possible mitigation effects that could be implemented as part of the design and installation of refrigeration units.

Conservative assumptions were generally employed in the present study to maximize the accumulated fuel volumes and ignition consequences. The purpose of using conservative assumptions is to identify the most effective mitigation effects. That is, a sufficiently effective mitigation measure for such conditions would also apply when such constraints are relaxed. The converse is not true—mitigation options that are effective under certain specific and extremely detailed conditions may not be effective in alternative situations. As such, analysis of mitigation options using a conservative approach is most useful when trying to make generic recommendations. This approach also provides a foundation for future work in which actual conditions are available. As such, the absolute risk determined in the present study likely represented an upper bound and will likely be reduced when considering details such as the transient nature of the leak and room ventilation. Therefore, due to the conservative assumptions and certain uncertainties associated with the leak frequencies, it is more appropriate to evaluate scenarios from a relative risk point of view as opposed to absolute risk. Absolute risk is still provided for some cases for informational purposes only, but the results should be used with caution.

5.1 Method

The general method of the risk assessment (Figure 5.1) is to:

1) Identify the assessment context including: operating modes, failure modes, and variables to evaluate (including charge sizes, hole sizes, condenser location, etc.)
2) Perform dispersion simulations to establish consequence results

3) Establish leak frequencies for various combinations of charges, hole sizes, and operating mode
4) Establish an ignited event frequency to be associated with each possible incident (or unique combination of variables and hazard) that results in a consequence
5) Calculate the risk by combing the incident frequencies with the associated consequences

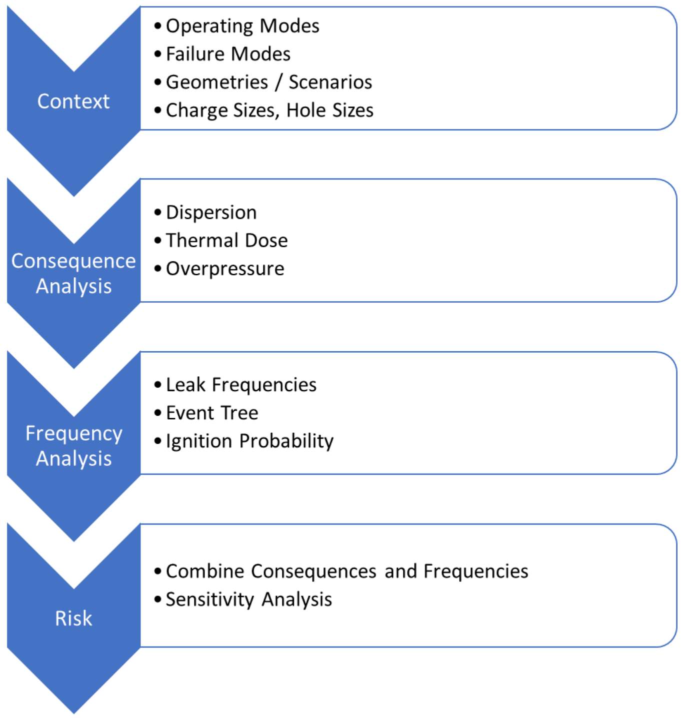


Figure 5.1: General Method of a Risk Assessment

The literature review, FMEA (see Appendix B), experiments, and CFD performed before the risk assessment work itself provided the context for determining the variables and inputs into the risk assessment itself.

5.2 Scenarios / Geometries

In order to ensure that the risk assessment has a wide applicability to many situations, the risk assessment was performed for six different scenarios that represented a variety of real-world situations relevant to the use of refrigerated display cases. The scenarios were selected to represent a cross-section in purpose, room size, aspect ratio (the ratio of the length to the width of the room floor area), and congestion characteristics.

The six scenarios are shown in Table 5.1. The maximum charge size range in the table is based on EN-378, which allows 20% LFL times the room volume, up to 1.5 kg (3.3 lb).

Table 5.1: Risk Assessment Scenarios / Geometries

No.	Description	Area m^2 (ft^2)	Volume m^3 (ft^3)	Aspect Ratio	EN-378 Maximum Charge Size (g)
1	Small Convenience Store	11 (402)	30 (1059)	1.19:1	227
2	Small Kitchen	13 (441)	31 (1095)	0.50:1	238
3	Deli	28 (1000)	71 (2507)	3.75:1	538
4	Market	33 (1159)	90 (3178)	1.37:1	686
5	Medium Kitchen	56 (1978)	196 (6922)	0.88:1	1490
6	Big Box Grocery	256 (9041)*	1023 (36,127)*	1.00:1	1500

* The Big Box Grocery area and volume are for the relevant region of the store where refrigerated display cases are located and do not include the entire store.

The representations of refrigerated display cases in the scenarios are based on manufacturer information and details of the test unit provided for the full-scale testing (see Section3.2).

The first scenario is a small convenience store. Figure 5.2 shows images of the geometry for the small convenience store and relevant refrigerated cabinet from which releases were evaluated. The small convenience store is not quite square with an aspect ratio of 1.19:1 but is relatively square when compared to some of the other scenarios. A noteworthy feature of the small convenience store is that there is a counter that divides the room. It is also noteworthy that it is expected that there would be sparse ignition sources inside the convenience store. Figure 5.3 and Figure 5.4 show an additional view of the geometry and a view of the bottom of the refrigerated display case.

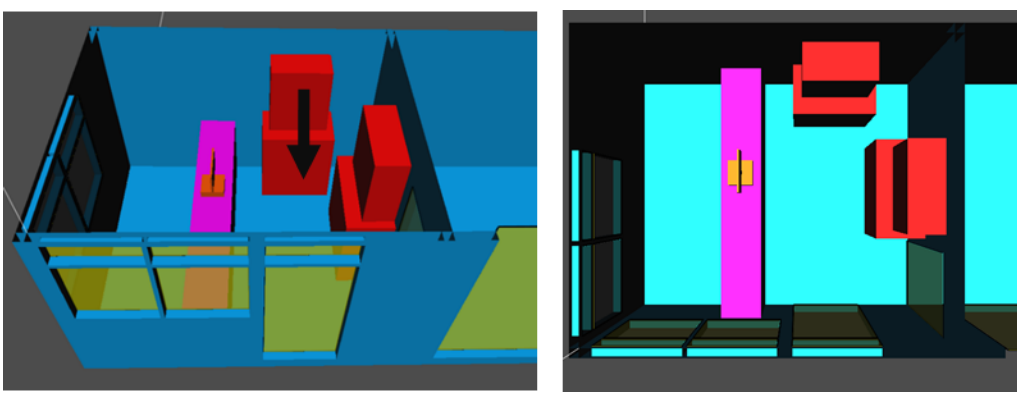


Figure 5.2: Risk Assessment Scenario #1 – Small Convenience Store

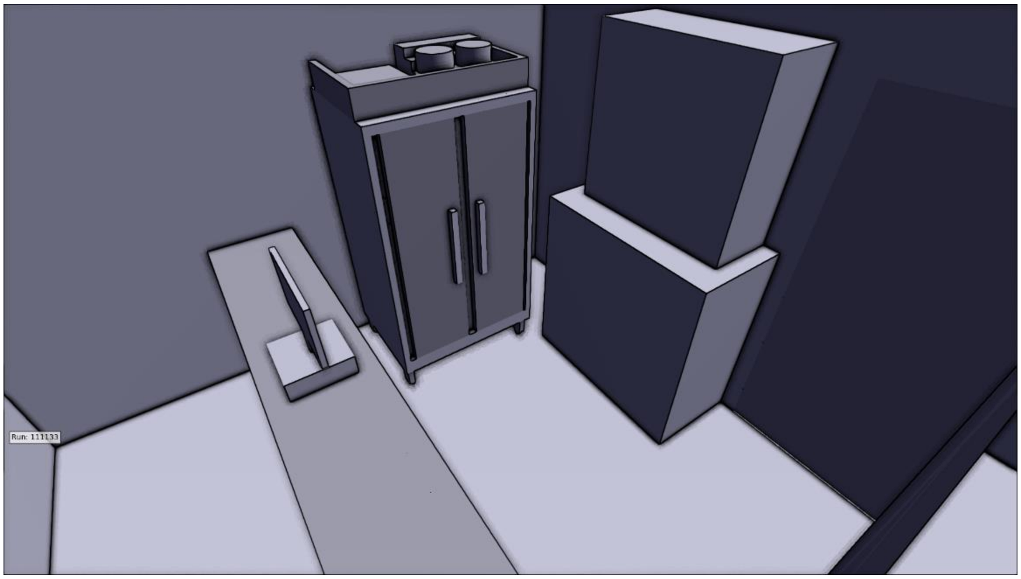


Figure 5.3: Risk Assessment Scenario #1 - Small Convenience Store – Perspective #1

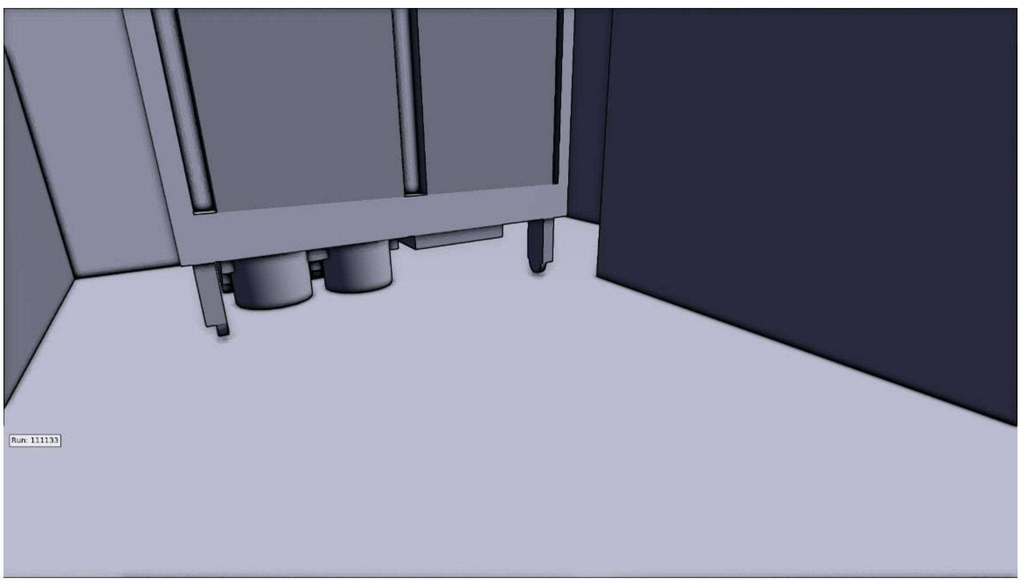


Figure 5.4: Risk Assessment Scenario #1 - Small Convenience Store – Perspective #2

The second scenario is a small kitchen. Figure 5.5 shows images of the geometry for the small kitchen and relevant refrigerated cabinet from which releases were evaluated. The small kitchen is a very narrow rectangular shape with an aspect ratio of 0.50:1. As this geometry represents a kitchen, there are appliances and preparation stations lining the room. In addition, it is expected that there would be a reasonable amount of ignition sources due to open flames and appliances. Figure 5.6 and Figure 5.7 show an additional view of the geometry and a view of the bottom of the refrigerated display case.

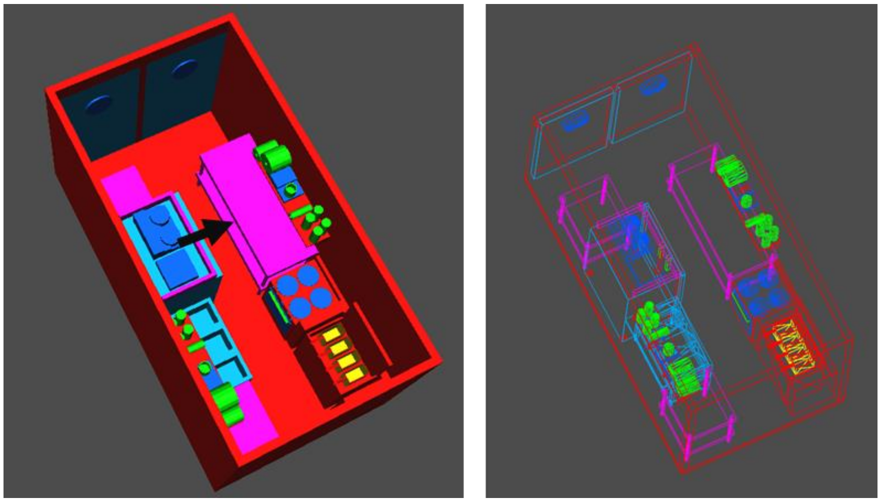


Figure 5.5: Risk Assessment Scenario #2 – Small Kitchen

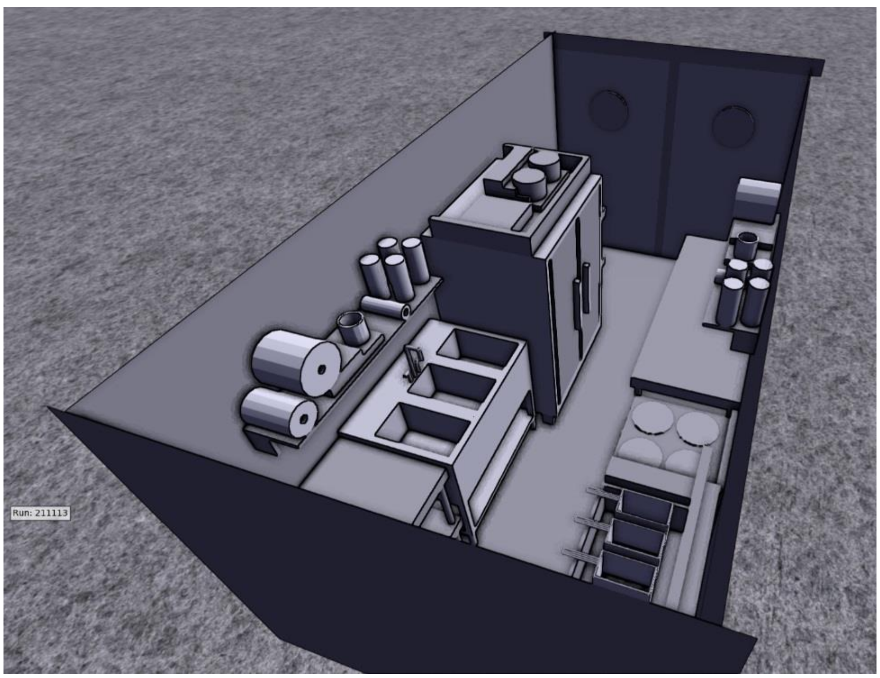


Figure 5.6: Risk Assessment Scenario #2 – Small Kitchen – Perspective #1

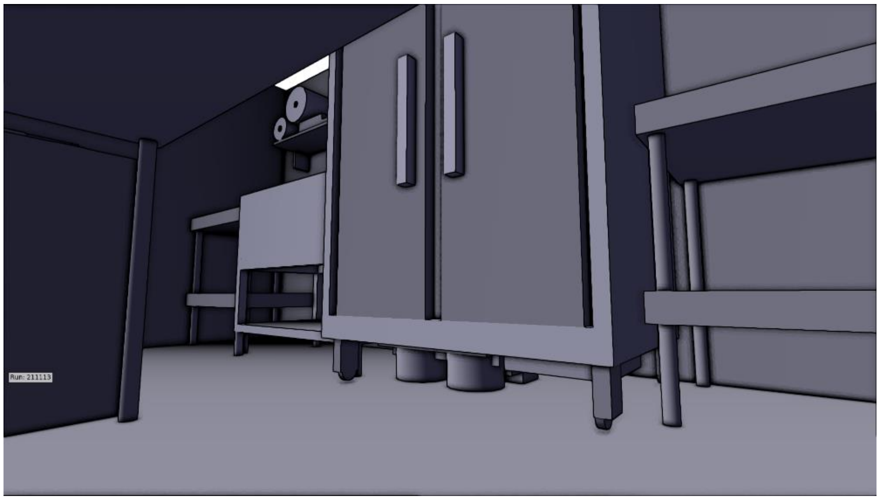


Figure 5.7: Risk Assessment Scenario #2 – Small Kitchen – Perspective #2

The third scenario is a small deli. Figure 5.8 shows images of the geometry for the small deli and relevant refrigerated cabinet from which releases were evaluated. The deli is a narrow rectangular shape with an aspect ratio of 3.75:1. The deli includes various congestion including tables and chairs that would be expected in a small shop that sells quick, prepared foods. As with the convenience store, it was expected that ignition sources would be sparse inside the deli. Figure 5.9 and Figure 5.10 show an additional view of the geometry and a view of the bottom of the refrigerated display case.

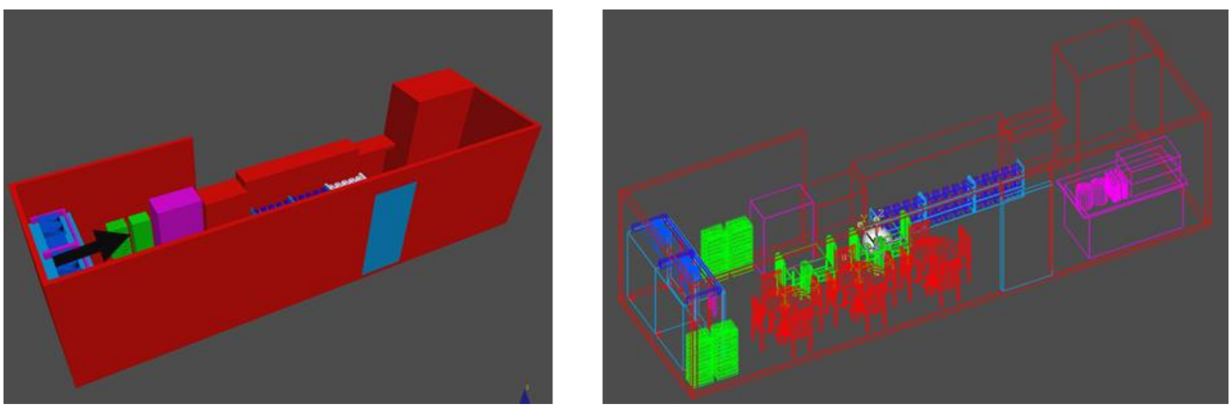


Figure 5.8: Risk Assessment Scenario #3 – Deli

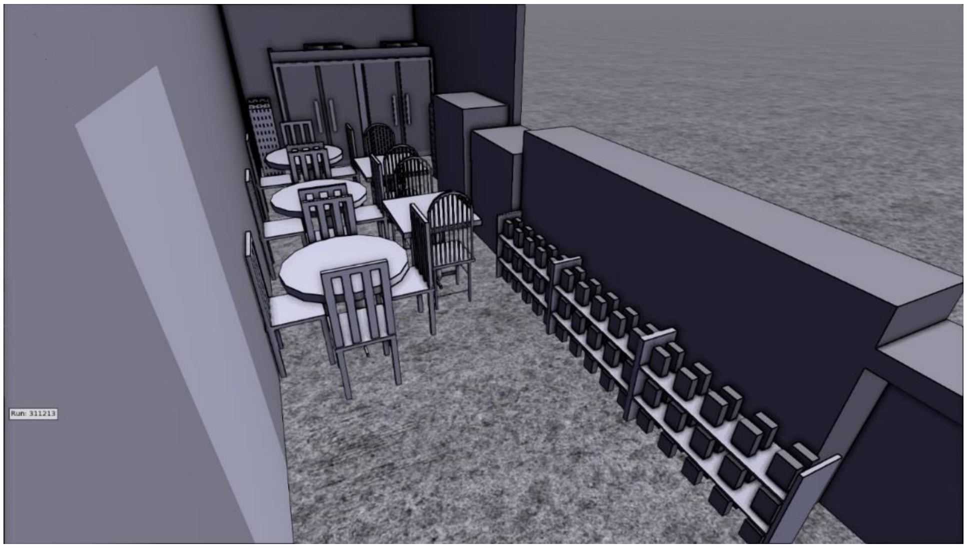


Figure 5.9: Risk Assessment Scenario #3 – Deli – Perspective #1

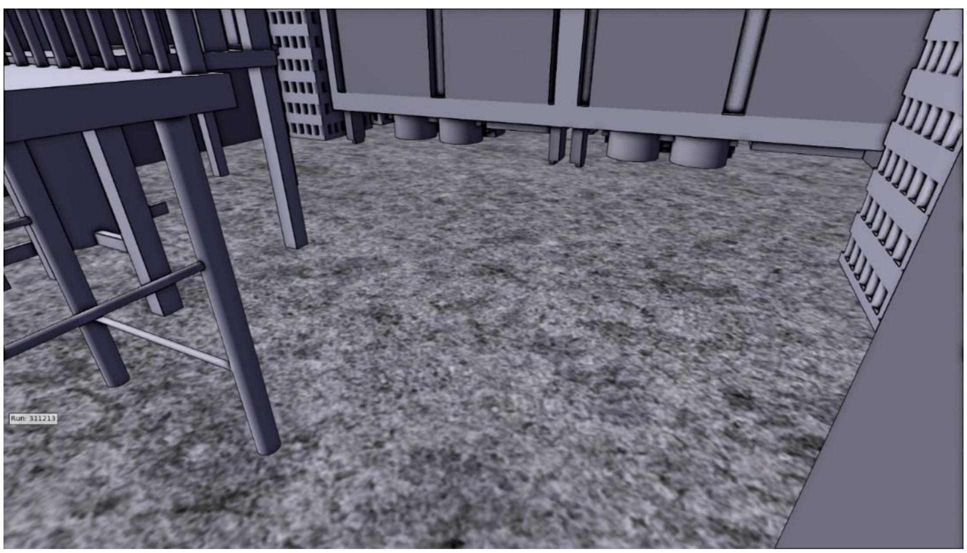


Figure 5.10: Risk Assessment Scenario #3 – Deli – Perspective #2

The fourth scenario is a market. Figure 5.11 shows images of the geometry for the market and the relevant refrigerated cabinet from which releases were evaluated. The market is a relatively square area with an aspect ratio of 1.37:1. The market includes a variety of obstructions include tall shelves that divide the room. The room is also lined with display cases and contains a wheelchair ramp at the entrance. As with the deli and convenience store, it was expected that ignition sources would be sparse inside the market. Figure 5.12 and Figure 5.13 show an additional view of the geometry and a view of the bottom of the refrigerated display case. The red arrow in the figures indicates the display case from which leaks originate.

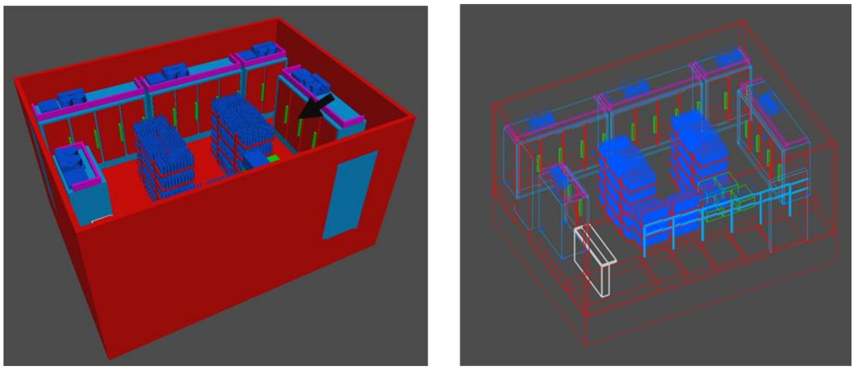


Figure 5.11: Risk Assessment Scenario #4 – Market

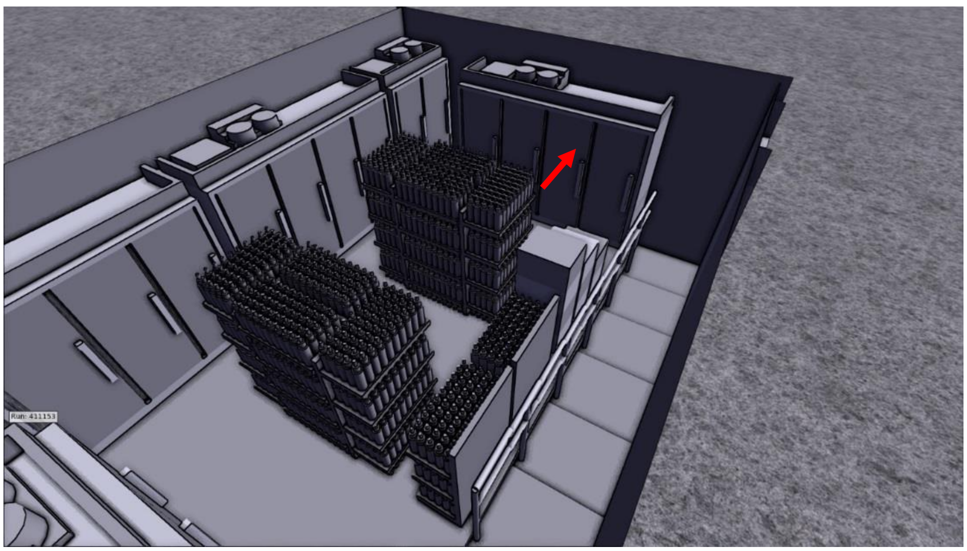


Figure 5.12: Risk Assessment Scenario #4 – Market – Perspective #1 (red arrow indicates which display case leaks)

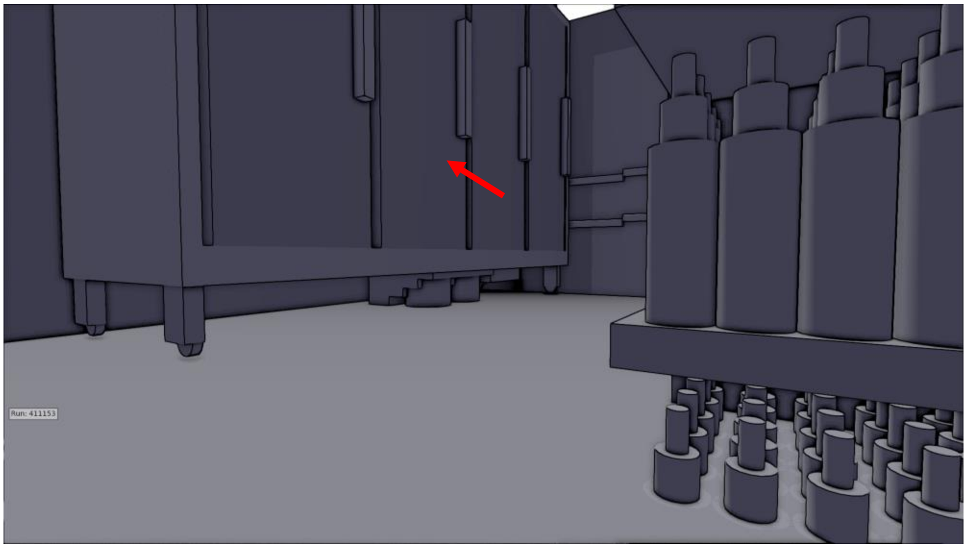


Figure 5.13: Risk Assessment Scenario #4 – Market – Perspective #2 (red arrow indicates which display case leaks)

The fifth scenario is a medium kitchen. Figure 5.14 shows images of the geometry for the medium kitchen and the relevant refrigerated cabinet from which releases were evaluated. The kitchen is relatively square with an aspect ratio of 0.88:1. Like the small kitchen, the walls are lined with appliances; however, preparation stations are included in the middle of the kitchen since there is enough room. And although there are multiple vent hoods represented in this geometry, the risk assessment does not account for the ventilation due to these vent hoods. As with the small kitchen, it is expected that there would be higher density of ignition sources. Figure 5.15 and Figure 5.16 show an additional view of the geometry and a view of the bottom of the refrigerated display case.

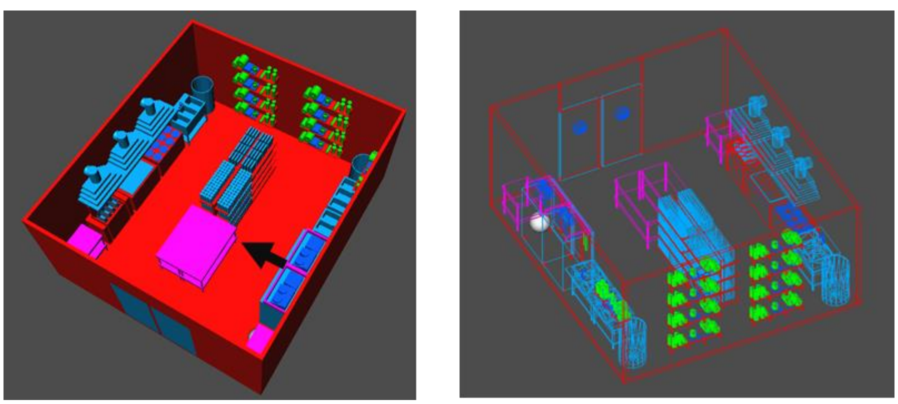


Figure 5.14: Risk Assessment Scenario #5 – Medium Kitchen

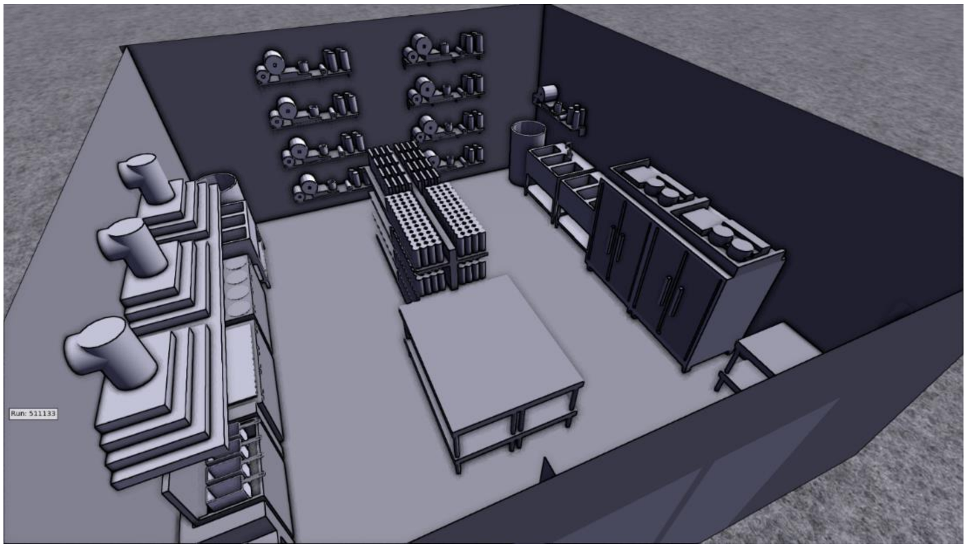


Figure 5.15: Risk Assessment Scenario #5 – Medium Kitchen – Perspective #1

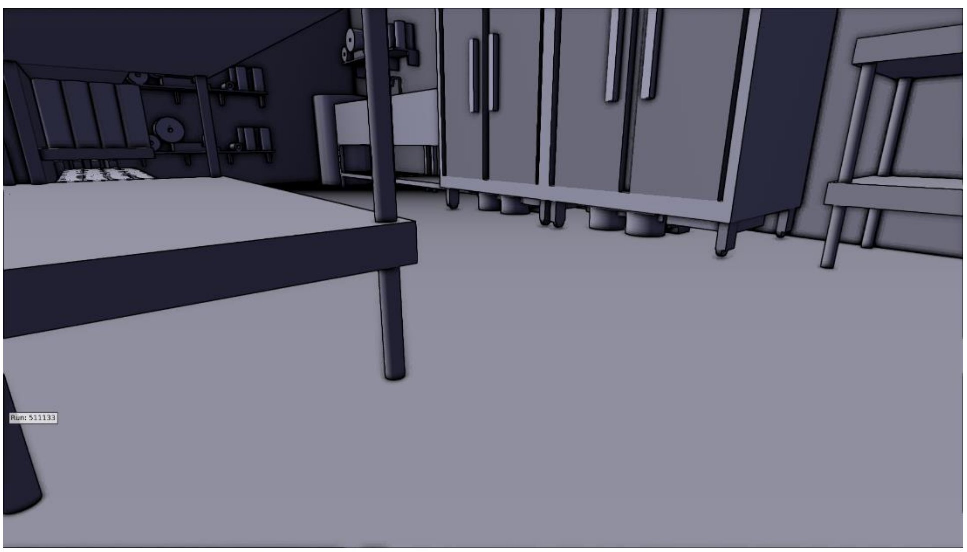


Figure 5.16: Risk Assessment Scenario #5 – Medium Kitchen – Perspective #2

The sixth scenario is a big box grocery store. Figure 5.17 shows images of the geometry for the big box grocery store and relevant refrigerated cabinet from which releases were evaluated. The grocery store is a very large, square room that include multiple aisles containing display cases, shelves, and items. The aisles in this scenario are larger and less dense than those in the market. As with the market, it is expected that were would be reasonably sparse ignition sources inside the store. Figure 5.18, Figure 5.19, and Figure 5.20 show additional views of the geometry and the bottom of the refrigerated display case. The red arrow in the figures indicates the display case from which leaks originate.

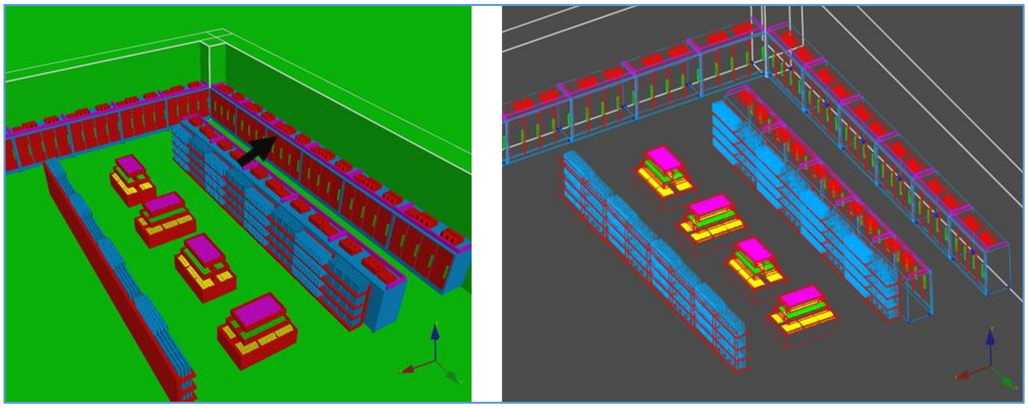


Figure 5.17: Risk Assessment Scenario #6 – Big Box Grocery Store

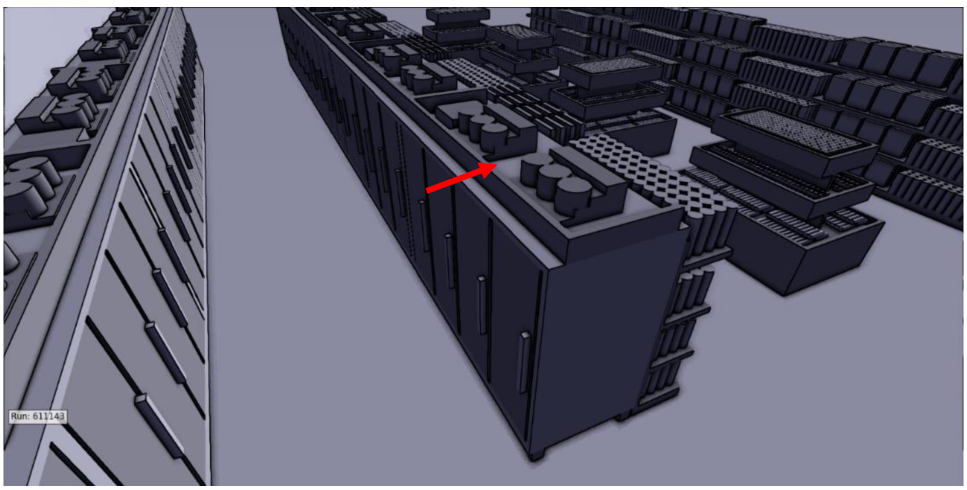


Figure 5.18: Risk Assessment Scenario #6 – Big Box Grocery Store – Perspective #1 (red arrow indicates which display case leaks)

Figure 5.19: Risk Assessment Scenario #6 – Big Box Grocery Store – Perspective #2 (red arrow indicates which display case leaks)

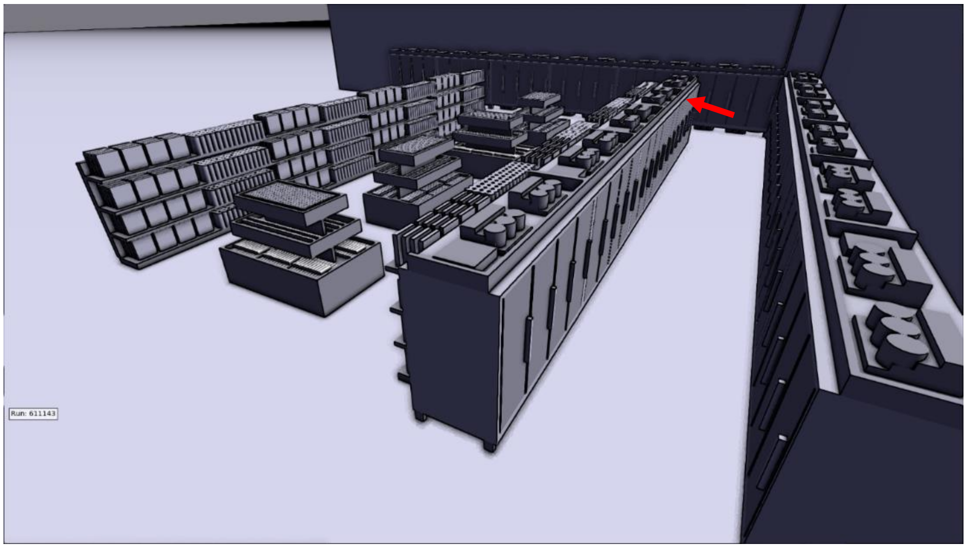


Figure 5.20: Risk Assessment Scenario #6 – Big Box Grocery Store – Perspective #3 (red arrow indicates which display case leaks)

5.3 Consequence Analysis

The consequence analysis component of the risk assessment was designed based on utilizing the work discussed in the preceding sections. The consequence analysis involves three main components:

1) Accumulated fuel volumes and jet plumes obtained through a thorough battery of CFD dispersion simulations for each of the six scenarios / geometries described in Section 5.2
2) Thermal dose results calculated via a correlation for thermal exposure (measured as thermal dose, as explained in Section 3.5) based on the experimental results
3) Overpressure results calculated via a correlation for overpressure based on CFD results

5.3.1 CFD Dispersion

CFD dispersion simulations can be used to characterize how accumulated fuel volumes form during a leak, and to quantify specific properties that correlate to post-ignition event severity. These properties include the accumulated fuel volume with R-290 concentrations above LFL (i.e., the contributing part of the layer) as well as the mass of R-290, average concentration of R-290, and degree of concentration uniformity in the contributing fuel layer. Note that the contributing fuel layer is the volume of all fuel concentrations above LFL and not the just the volume within the flammability limits (i.e., between LFL and UFL). Recall that the room-scale experiments showed that rich layers (greater than UFL) contribute to the post-ignition event severity by burning as diffusion flames after ignition occurs in a layer where the concentration is within the flammability limits.

A series of more than 600 CFD simulations were run to establish the following variables for the risk assessment:

1) The size of the accumulated fuel volume (as defined in Section 2.2)
2) The average concentration of R-290 in the accumulated fuel volume

There were essentially three groups of dispersion simulations that were used as input to the risk assessment:

1) Representative jet leaks (as discussed in Section 2.4)
2) Impinged / diffuse leaks
3) In-cabinet releases

The representative jet leaks were not considered to result in accumulated fuel volumes provided the charge size was appropriately selected for the room—as discussed in Section 2.4—and therefore do not accumulate in regions remote to the leak source.

Table 5.2 describes the various parameters for the diffuse leaks. Diffuse leaks represent the most common leak scenarios and therefore cover a wide range of data. Diffuse leaks were simulated for all geometries, top and bottom-mounted condenser refrigeration units, five leak rates, and five charge sizes. The simulations that included fans used a fan flow rate of 1 m^3 / hour for every 1 g of charge, and it was assumed that the fans remained either on or off for the duration of the leak. As these leaks were represented as diffuse leaks, they represented conservative, worst-case leaks that did not include any effect of mixing due to the momentum of the leak itself.

Table 5.2: Risk CFD Dispersion Simulation Matrix – Diffuse Leaks

Parameter	**Count**	**Variations**
Geometry	6	Six geometries as described in Section 5.2
Condenser Location	2	Top, Bottom
Leak Rate	5	10, 60, 120, 250, 500 g/min (0.02, 0.13, 0.26, 0.55, 1.1 lb/min)
Charge Size	5	150, 300, 450, 600, 1000 g (0.33, 0.66, 0.99, 1.32, 2.2 lb)
Fan Status	2	On, Off

The general trends of the dispersion results are aligned with the findings discussed in the previous sections.

Figure 5.21 shows an example that there is generally better mixing for leaks from the top of a unit, even without fans, when compared to leaks from the bottom. The figure shows a comparison between a top and bottom leak of a 600 g (1.32 lb) charge in geometry No. 4 at 120 g/min (0.26 lb/min) without fans. For the top leak (top half of figure), the leak is able to spread reasonably far with a concentration near LFL. However, the bottom leak (bottom half of figure) covers a similar footprint but with a higher concentration at the floor level since there is less mixing due to the leak height.

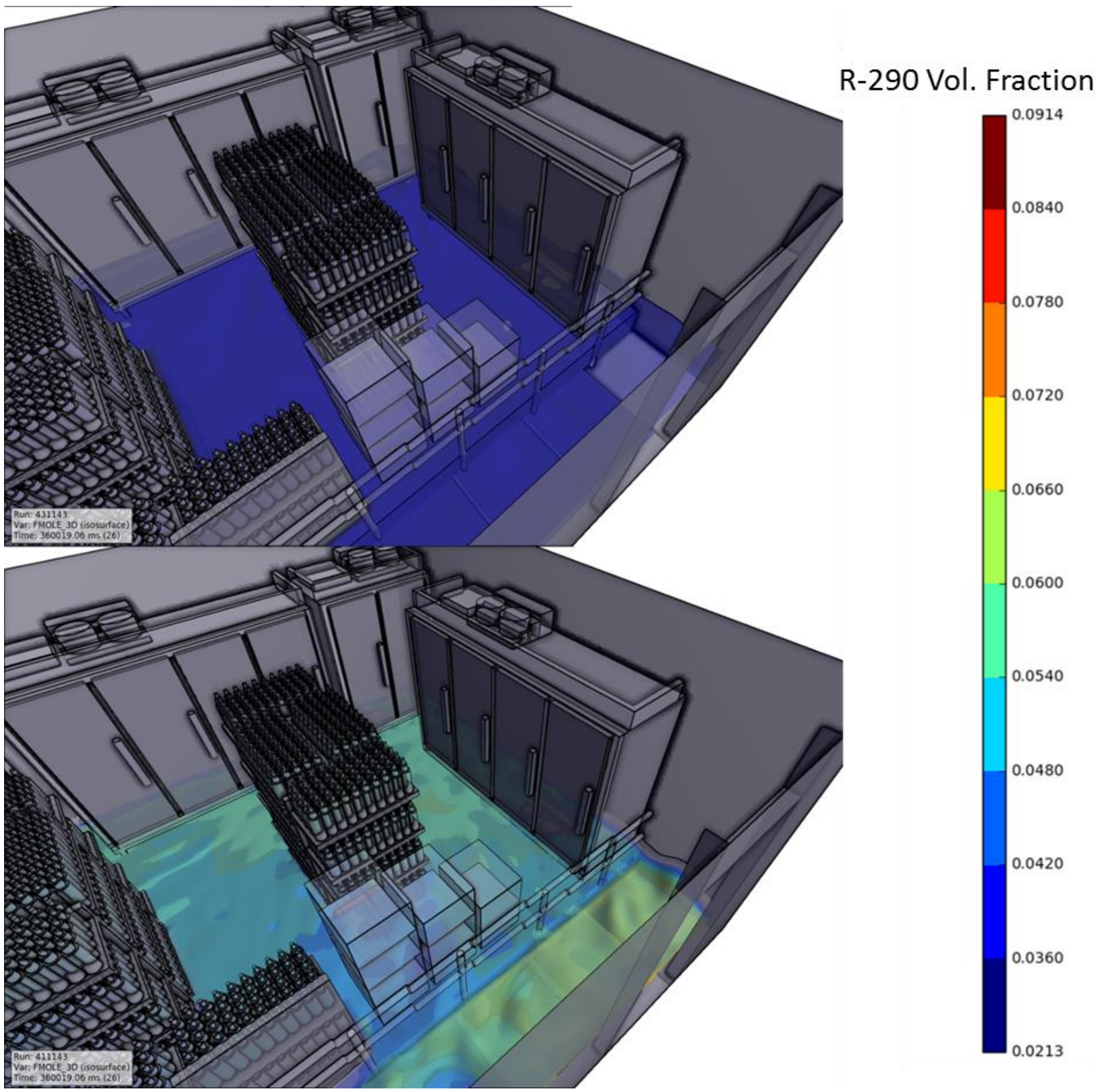


Figure 5.21: Risk Simulations - 120 g/min (0.26 lb/min) leak of 600 g (1.32 lb) in Geometry No. 4 from top (top half of figure) compared with bottom (bottom half of figure)

Figure 5.22 shows an example of the impact that fans can have on the accumulated fuel volume. The figure shows a comparison between a 150 g (0.33 lb) bottom leak in geometry No. 1 at 60 g/min (0.13 lb/min) with and without fans. When the fans are off (bottom half of figure), the leak is able to accumulate in the room below and in front of the cabinet. When fans are on (top half of figure), there is effectively no accumulation of flammable mass and the only sign of the leak is in a small patch behind the cabinet.

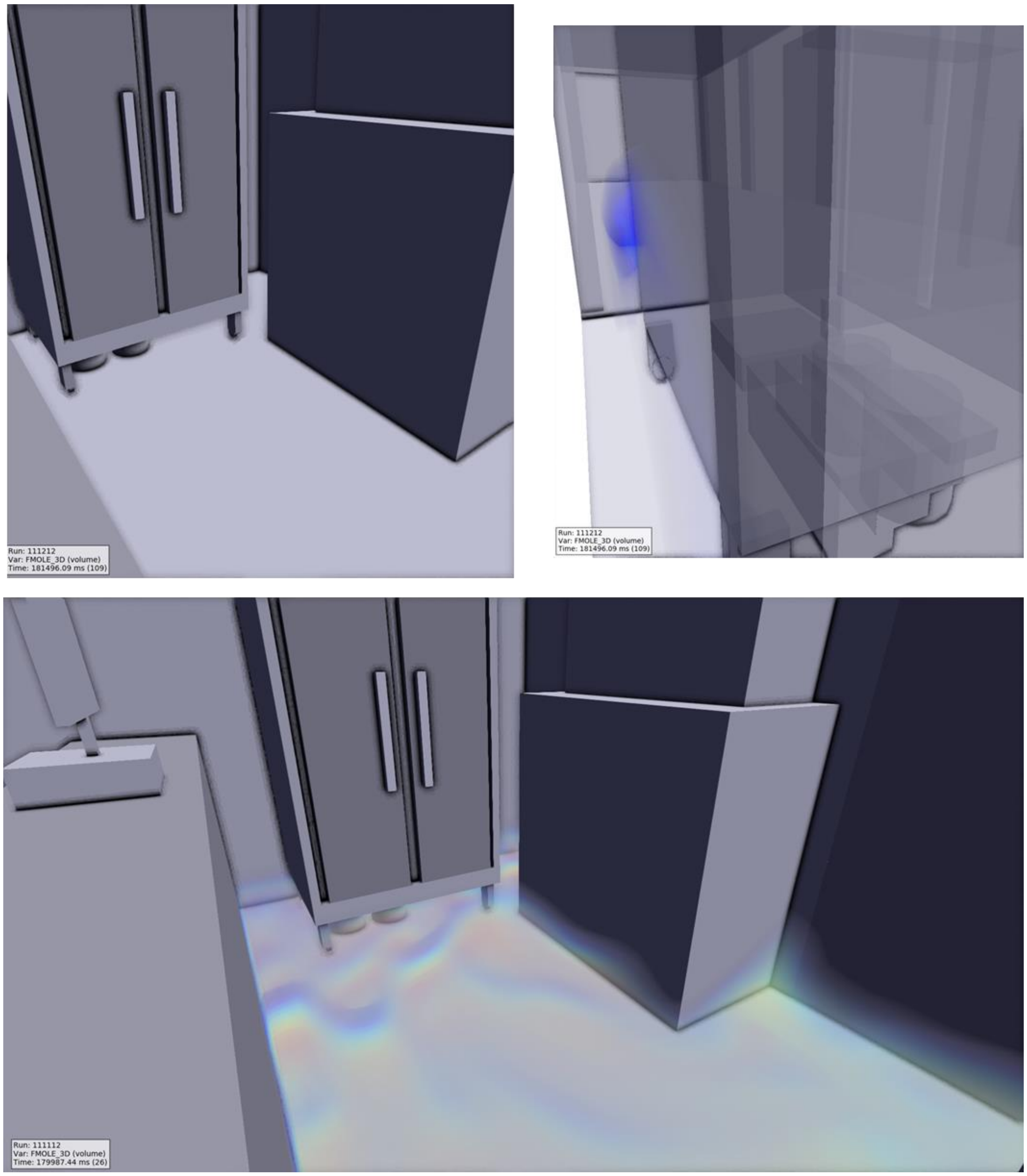


Figure 5.22: Risk Simulations - 60 g/min (0.13 lb/min) bottom leak of 150 g (0.33 lb) in Geometry No. 1 with fans (top) compared to without fans (bottom)

In-cabinet releases were represented by a series of varying cabinet volumes that varied with charge size. Table 5.3 describes the parameters for the in-cabinet leaks. In-cabinet leaks were taken to be either impinged (diffuse) or a jet. Diffuse leaks were simulated at 10 g/min (0.02 lb/min) inside the cabinet because the layering inside of a closed cabinet were generally insensitive to leak rates (when the whole charge was leaked) and lower leak rates would be more likely. Jet leaks were represented as a homogeneous mixture containing the entire charge contained inside the cabinet before the door was opened. The results for in-cabinet releases were established by simulating the dispersion that occurred after opening the door of a filled cabinet and taking the results at the time with the maximum accumulated fuel volume size.

Table 5.3: Risk CFD Dispersion Simulation Matrix – In-cabinet Leaks

Parameter	Count	Variations
Geometry	5 / 10	Five geometries to represent different size display cases per charge size (with variations of both the door open and closed)
Leak Rate	2	10 g/min (diffuse), jet
Charge Size	5	150, 300, 450, 600, 1000 g (0.33, 0.66, 0.99, 1.32, 2.2 lb)

The internal dimensions of the cabinets for in-cabinet leaks were scaled based on the charge and shown in Table 5.4. These dimensions and internal volumes were based on manufacturer specifications provided by the panel that related charge size with dimensions of a product line of real cabinets.

Table 5.4: Risk CFD Dispersion Simulations – In-cabinet Leaks – Representative Cabinet Dimensions

Charge Size	Internal Volume m^3 (ft^3)	Dimensions m (ft)
150g	0.54 (19.1)	0.85m x 0.85m x 0.75m (2.8' x 2.8' x 2.5')
300g	0.80 (28.1)	0.85m x 0.85m x 1.10m (2.8' x 2.8' x 3.6')
450g	1.12 (39.5)	0.85m x 0.85m x 1.55m (2.8' x 2.8' x 5.1')
600g	1.51 (53.5)	1.15m x 0.85m x 1.55m (3.8' x 2.8' x 5.1')
1000g	4.59 (165.2)	3.55m x 0.85m x 1.55m (11.6' x 2.8' x 5.1')

Table 5.5 summarizes the simulation results for volume above LFL in the domain (i.e., the accumulated fuel volume) and the average R-290 concentration calculated in the accumulated fuel volume for in-cabinet leak simulations after the door is opened.

Table 5.5: Risk CFD Dispersion Simulations – In-cabinet Leaks – Results Summary

Charge Size	Diffuse Leaks		Jet Leaks	
	Volume > LFL (m^3)	Avg. Conc.	Volume > LFL (m^3)	Avg. Conc.
150g	1.12	6.9%	1.20	6.4%
300g	1.78	8.4%	1.97	8.0%
450g	2.42	9.3%	2.70	8.7%
600g	3.14	9.6%	3.10	10.3%
1000g	4.84	11.3%	9.26	5.3%

Figure 5.23 shows the varying display case sizes for the in-cabinet releases as well as the maximum accumulated fuel volumes for the diffuse releases after the doors are opened. The scale is from blue representing LFL through red representing UFL or greater.

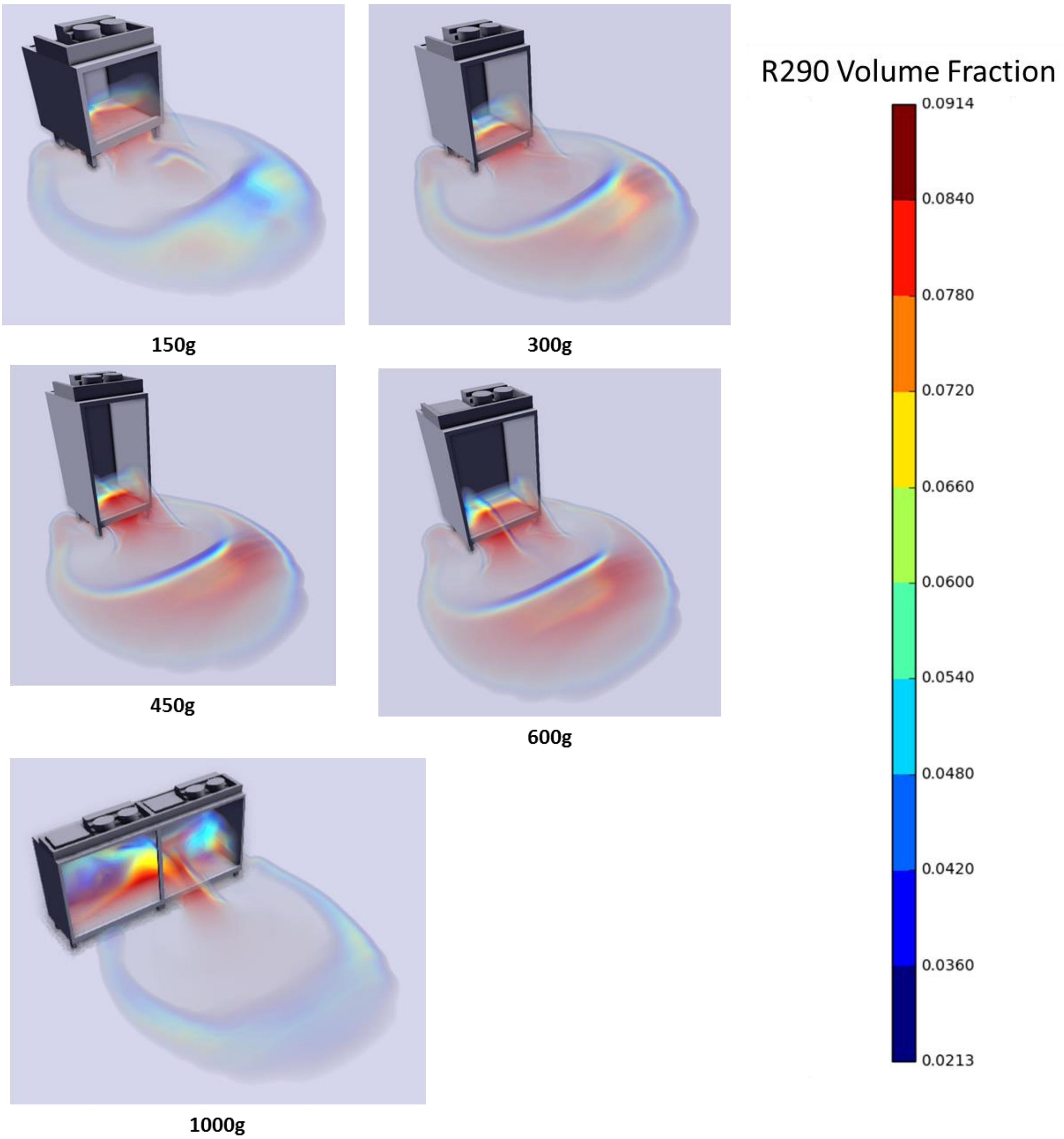


Figure 5.23: In-cabinet Release Geometries with Largest Clouds (Diffuse Leaks)

Figure 5.24 shows the same display cases as Figure 5.23; however, with the corresponding maximum accumulated fuel volumes for jet leaks inside the cabinet.

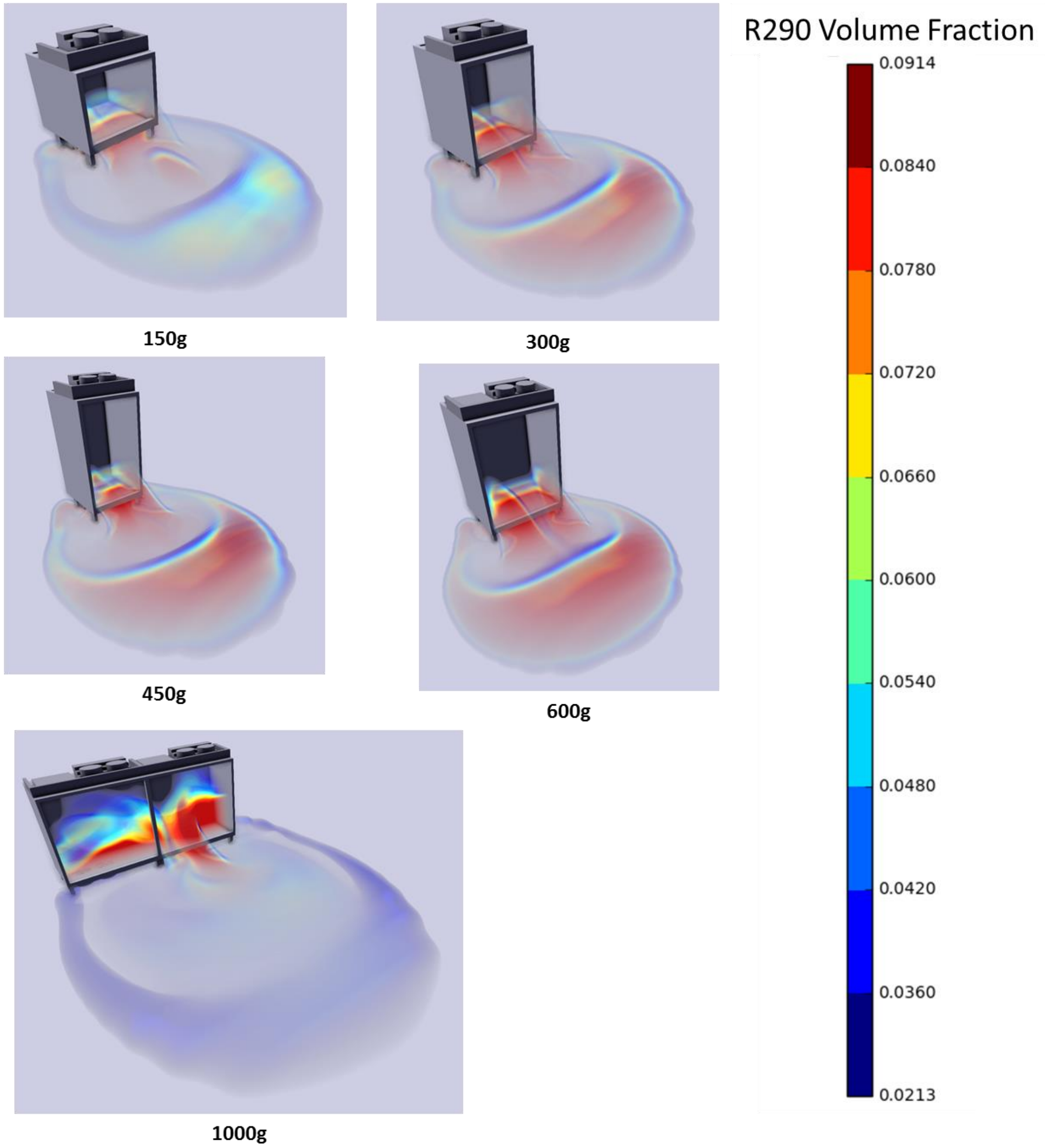


Figure 5.24: In-cabinet Release Geometries with Largest Clouds (Jet Leaks)

An important feature to note regarding the in-cabinet releases is that the R-290 trapped inside the cabinet mixes quickly into the room volume once the door is opened — generally in a few seconds, as shown in Figure 5.25.

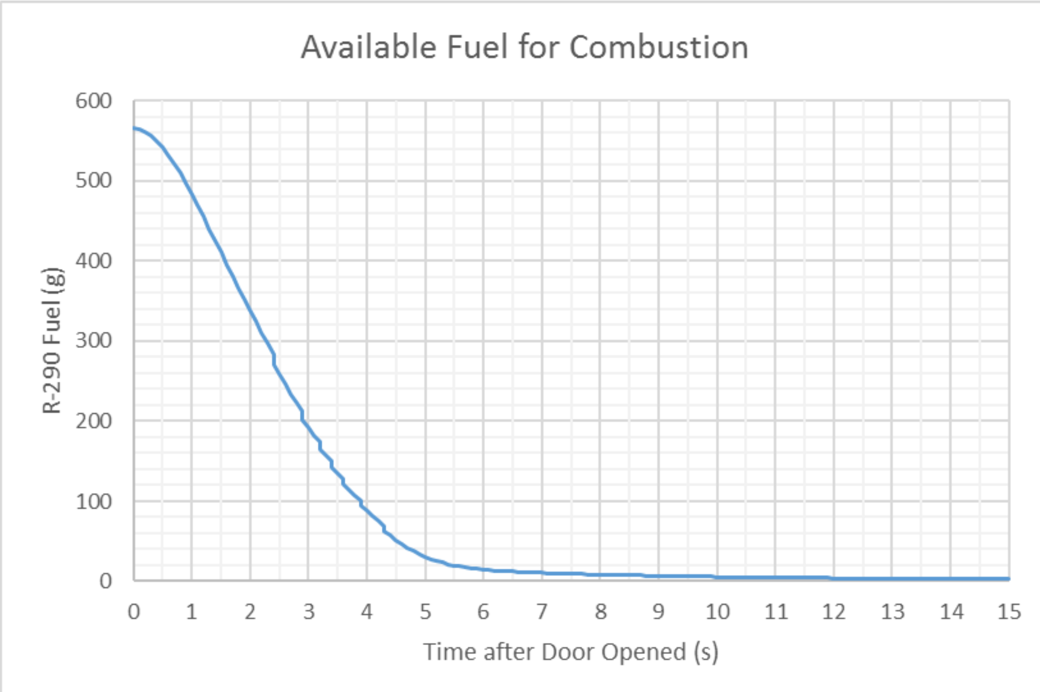


Figure 5.25: Fuel available for combustion after opening the door of a cabinet after filled by a 600g diffuse leak inside the cabinet

However, the results for the risk study are conservatively taken from the time corresponding with the maximum accumulated fuel volume.

5.3.2 Thermal Dose

Using the thermal dose data obtained from the experiments (see Section 3.5) combined with the CFD dispersion simulations of the ignited tests (see Section 4), a correlation was created to estimate the thermal dose based on details about the accumulated fuel volume. Therefore, the thermal dose relation used in the present study is based on an individual being in the proximity of the accumulated fuel volume after ignition.

Figure 5.26 shows the correlation that was created by combining the data from both sources. The correlation fits the data reasonably well and provides a simple and robust approach to estimate thermal dose within the domain of this assessment.

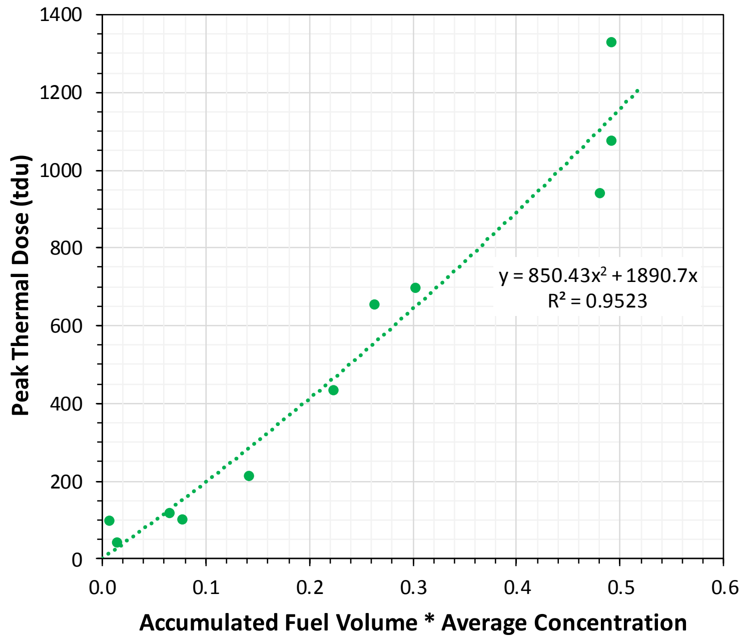


Figure 5.26: Correlation between peak thermal dose measured in the experiments and contributing volume (the product of accumulated fuel volume and the average concentration) at the time of ignition determined from FLACS dispersion simulations of the experiments.

5.3.3 Overpressure

The following approach was used to establish a relationship between overpressure and the results of the dispersion simulations:

1. Perform several hundred explosion simulations with defined accumulated fuel volumes varying:
    a. Heights
    b. Concentration gradients
    c. Amount of R-290 mass
    d. Different geometries, all without venting paths and with non-yielding walls
    e. Ignition locations
2. Extracted peak pressure rise from each simulation
3. For each scenario, only considered the maximum pressure rise from all ignition locations
4. Extracted volume above LFL (i.e., accumulated fuel volume), and average concentration within the volume above LFL
5. Determined the ratio of accumulated fuel volume to room volume
6. Determined the expansion factor as a function of R-290 concentration from constant pressure equilibrium calculations
7. Based on the idea that accumulated fuel volumes are uniform at the average concentration, apply the expansion factor to the ratio of accumulated fuel volume to room volume

8. This approach resulted in two distinct correlations because high gradient clouds with fuel-rich layers above the UFL at the floor are not well represented by uniform layers at the average concentration
9. FLACS simulates the pool fire nature of the rich layers and therefore for a given value on the x-axis, the pressures are lower for the fuel-rich layers above the UFL compared to the flammable layers.

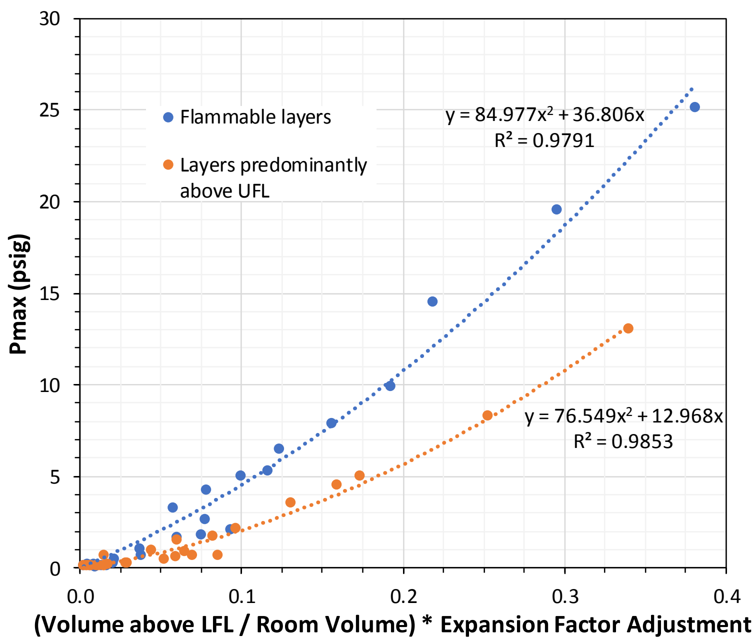


Figure 5.27: Correlations for pressure rise based on the accumulated fuel volume, room volume, and average concentration of R-290 in the accumulated fuel volume.

5.4 Frequency Analysis

5.4.1 Leak Frequencies

The base data and approach for the leak frequencies were derived from industry sources [17, 18]. Accounting for the connections based on the descriptions in both sources, the leak frequency for small, medium, and catastrophic leaks per cabinet-year were calculated to be 5.70E-04, 3.45E-05, and 4.32E-06 respectively. However, the base data source accounted for compressor always on, so the base leak frequencies had to be adjusted to account for the compressor on/off time.

Leak frequencies were calculated assuming that the compressor was on 60% of the time and that the likelihood of leaks due to medium and large hole sizes were reduced while the compressor was idle. Based on the FMEA, there is a reduction in the possible failure modes that result in leaks while the compressor is idle. When the compressor is idle, the dominating failure modes are fatigue and stress/corrosion/cracking which are skewed towards smaller hole sizes. As such, the likelihood of small leaks remained the same regardless of the compressor status, but the likelihood of large leaks was reduced by 50% while the compressor is idle. Taking this into account, the adjusted leak frequencies for small, medium, and catastrophic leaks were calculated to be 5.63E-04, 3.07E-05, and 3.41E-06 per cabinet per year.

The leak frequency was determined to vary with charge size since the amount of piping in a refrigerated cabinet varies with charge size based on data provided by the technical panel. Table 5.6 summarizes the provided data. Based on the provided information, an average length of piping per gram of charge was established as 0.098 m per gram to estimate the effect of piping length on leak frequency.

Table 5.6: Average Piping Lengths for Various Charge Sizes

Charge Size	Average Piping Lengths (m)		
	Vapor	Two-Phase	Liquid
150g	5.50	7.75	1.00
300g	10.25	17.00	1.25
600g	20.00	35.00	2.00
1000g	35.50	67.00	3.50

Further, the leak frequencies needed to be distributed into a range of hole sizes for the risk assessment. Table 5.7 shows the resulting leak frequencies for each hole size and charge size combinations.

Table 5.7: Leak Frequencies by Hole Size and Charge Size

Hole Size (mm)	150g	300g	450g	600g	1000g
0.1	3.97E-04	4.96E-04	5.95E-04	6.94E-04	9.58E-04
0.2	1.09E-04	1.37E-04	1.64E-04	1.91E-04	2.64E-04
0.3	5.15E-05	6.44E-05	7.73E-05	9.01E-05	1.24E-04
0.5	1.99E-05	2.49E-05	2.99E-05	3.49E-05	4.82E-05
0.7	1.07E-05	1.33E-05	1.60E-05	1.87E-05	2.58E-05
1	5.50E-06	6.88E-06	8.25E-06	9.63E-06	1.33E-05
1.5	2.59E-06	3.24E-06	3.88E-06	4.53E-06	6.26E-06
3	7.14E-07	8.93E-07	1.07E-06	1.25E-06	1.73E-06
9	9.28E-08	1.16E-07	1.39E-07	1.62E-07	2.24E-07

Table 5.8 shows the contribution of each hole size to the total leak frequency as well as the relevant vapor and liquid leak rates for reference. It's relevant to keep in mind that the risk assessment considered both vapor and liquid releases—and the same leak rate is associated with different hole sizes for vapor and liquid releases. The risk assessment assumed that all vapor releases came from the high-pressure side of the refrigeration cycle for the purpose of establishing the relationship between hole size and leak rate.

Table 5.8: Contribution to Leak Frequency by Hole Size with Vapor and Liquid Leak Rates

Hole Size (mm)	Percent Contribution	Leak Rates (g/min)	
		Vapor	Liquid
0.1	66.43%	2.3	11.6
0.2	18.33%	9.2	46.6
0.3	8.63%	20.8	104.8
0.5	3.34%	57.8	291.0
0.7	1.79%	113.3	570.4
1	0.92%	231.2	1164.0
1.5	0.43%	520.2	2619.0
3	0.12%	2080.8	10476.0
9	0.02%	18727.2	94284.0

Table 5.9 shows the mapping between risk assessment hole sizes and the leak frequency hole sizes for vapor and liquid releases. The risk assessment classifies events as seven hole sizes that are represented differently for vapor and liquid releases.

Table 5.9: Mapping of Leak Frequency Hole Sizes for Vapor and Liquid Releases to Risk Assessment

Risk Assessment Hole Size ID	Representative Hole Size (mm)			
	Vapor - Impinged	Liquid - Impinged	Vapor - Free	Liquid - Free
H1	0.2	0.1	0.2	0.1
H2	0.5	0.2	0.5	0.2
H3	0.7	0.3	0.7	0.3
H4	1.0	0.5	1.0	0.5
H5	1.5	0.7	1.5	1.0
H6	3.0	3.0	3.0	3.0
H7	9.0	9.0	9.0	9.0

Figure 5.28 plots the leak frequencies shown in Table 5.7 and Figure 5.29 plots the accumulated leak frequencies.

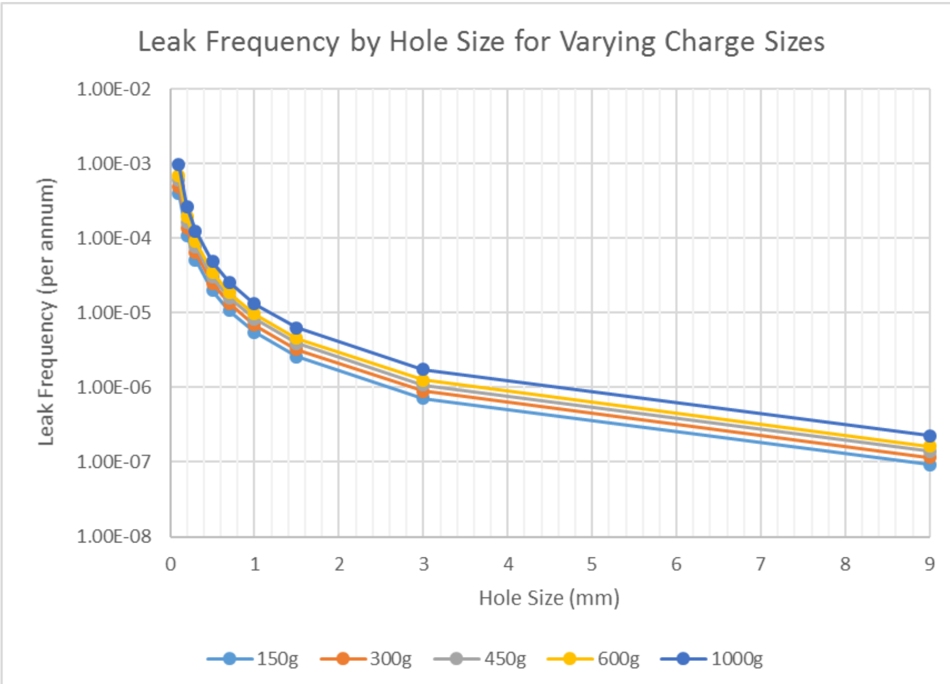


Figure 5.28: Leak Frequencies by Hole Size and Charge Size

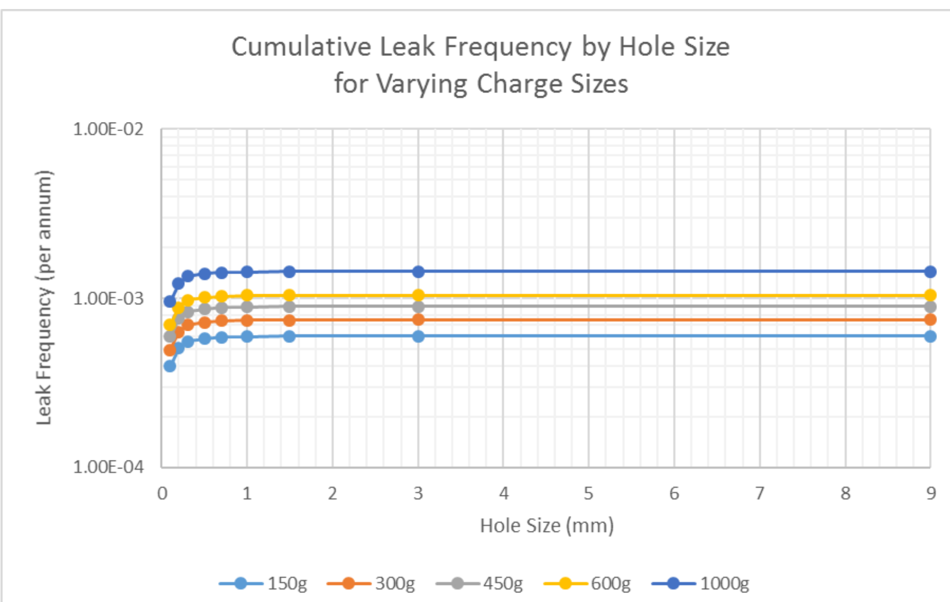


Figure 5.29: Cumulative Leak Frequencies

There is discussion on uncertainty regarding the leak frequencies in Section 5.5.

5.4.2 Event Trees

The risk assessment is based on calculating the frequency of many particular events and combing the results of these events to develop insight. In this case, these events are essentially unique combinations of variables.

Figure 5.30 shows a sample event tree for dispersion scenarios in the risk model. The event tree provides a visual illustration of how various variables interact in the model as part of calculating the frequency of various possible events. The variables included in the dispersion event tree are:

- Operating mode (normal operation or in-service)
- Leak frequency from Table 5.7 (which is a function of charge size and hole size and determined based on historical data)
- Whether the leak ends up inside or outside the cabinet
- Whether the leak is impinged or free
- Whether the leak is located at the condensing unit
- Whether the fans are on at the time of the leak

Expanding on the combinations of those variables yields the branches of the event tree for dispersion scenarios account for the following scenarios:

1) Impinged leak to the outside of the cabinet from condensing unit while fan(s) are on during normal operation of the cabinet
2) Impinged leak to the outside of the cabinet from condensing unit while fan(s) are off during normal operation of the cabinet
3) Impinged leak to the outside of the cabinet that does not come from the condensing unit during normal operation of the cabinet
4) Free jet leak to the outside of the cabinet during normal operation of the cabinet
5) Impinged leak to the inside of the cabinet during normal operation of the cabinet
6) Free jet leak to the inside of the cabinet during normal operation of the cabinet
7) Null branch that covers when a leak does not occur during normal operations
8) Impinged leak to the outside of the cabinet from condensing unit during servicing of the cabinet (fans are assumed off during servicing)
9) Impinged leak to the outside of the cabinet that does not come from the condensing unit during servicing of the cabinet (fans are assumed off during servicing)
10) Free jet leak to the outside of the cabinet during servicing of the cabinet
11) Impinged leak to the inside of the cabinet during servicing of the cabinet
12) Free jet leak to the inside of the cabinet during normal operation of the cabinet
13) Null branch that covers when a leak does not occur during servicing

For branch #3, fans are taken to have no effect on the leak because the leak occurs away from the condensing unit while the fans are located at the condensing unit. For branch #4, jet leaks are considered to not result in accumulate fuel volumes aside from the jet plume itself and are also assumed to be unaffected by fans. For branch #8, it is assumed that fans will be off or unavailable during servicing.

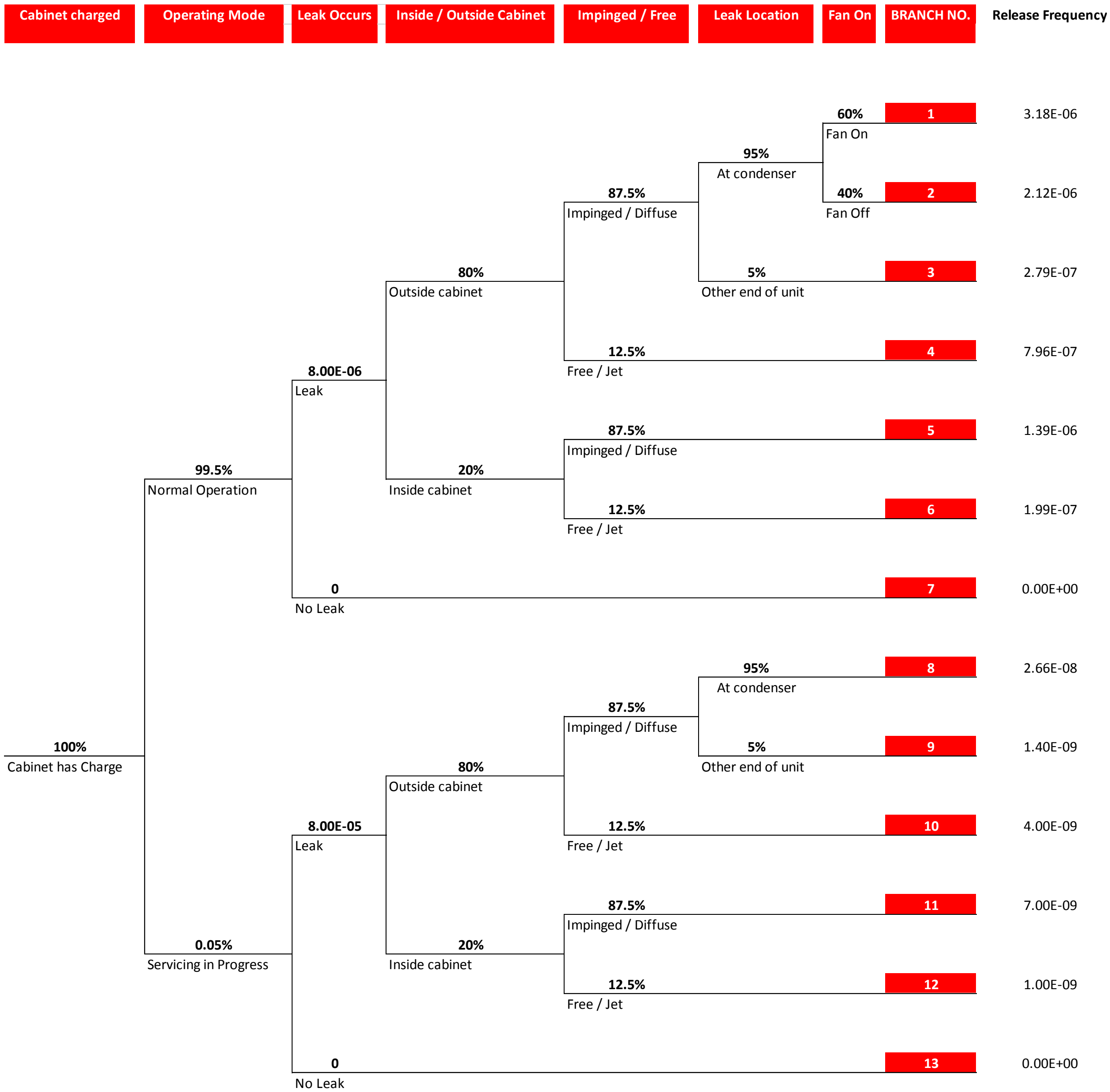


Figure 5.30: Sample Event Tree for Dispersion Events

The base case values for some of these parameters are displayed in Table 5.10.

Table 5.10: Base Case Parameter Inputs for Event Trees

Parameter	Base Case Value	Notes
Probability unit is being serviced	0.05%	Conservatively taken to be 4 hours per year
Probability leak is inside cabinet	20.0%	It is generally assumed that leaks occur outside the cabinet.
Probability leak is impinged	87.5%	For most possible leak orientations and locations, there would be a nearby obstruction—so impinged leaks would be expected to dominate.
Probability that external leak exits at the condenser height	95.0%	It is assumed that external leaks would generally exit from the condensing unit.

5.4.3 Ignition Probabilities

After combing the leak frequencies with the event tree for all possible input parameters, there is a range of unignited events with associated frequencies. The ignition probability is applied to these unignited events to create the ignited event frequency.

The ignition probability model used in this risk assessment is a simple model designed from a review of various sources [17-20]. Because the minimum ignition energy of R-290 is fairly low compared to A2L refrigerants, most ignition sources can be considered as potentially causing ignition of R-290. Because this assessment included CFD simulations to realistically represent the accumulated fuel footprint and volume of R-290 with concentrations greater than the LFL for each event in a series of realistic geometries, the accumulated fuel volume or volume greater than LFL in the domain was selected as an input to the ignition model. A benefit of this approach when compared to models used in other risk assessments (typically based on leak rate) is that this model better accounts for the different cloud accumulation characteristics between leaks from top-mounted and bottom-mounted units.

There are effectively three ignition probabilities:

1. Probability of ignition due to the interaction between the accumulated fuel volume and the ignition sources in the room geometry
2. Probability of ignition due to servicing (i.e. during recovery or venting)
3. Probability of ignition due to failure of internal components

The ignition probability in this risk assessment can be summarized as:

$P_{ign} = P_i + P_v \cdot V \cdot D + P_s$

where:

P_i = Probability of ignition due to internal components
P_v = Probability of ignition per cubic meter of R-290 greater than LFL
V = Accumulated fuel volume or volume of R-290 at concentrations greater than LFL in the dispersion results,
D = Density factor to account for density of ignition sources in scenario
P_s = Probability of ignition during servicing

The following values were used as inputs to the ignition model for the risk assessment:

- P_i = 0.1% to account for the likelihood of ignition due to internal components of the cabinet
- P_v = 0.1% per cubic meter of the accumulated fuel volume having concentrations greater than the LFL
- P_s = 5% if the event occurs during servicing
- D = 1 for all non-kitchen scenarios;
- D = 20 for kitchen scenarios

An important note regarding the calculation of ignition probability is that although jet plumes were not considered to result in flammable clouds remote from the leak and therefore have minimal accumulation (see Section 2.4), the contribution of the plume itself to accumulated fuel volume was accounted for when calculating the ignition probability for the various scenarios. By accounting for the effect of the jet plume in the ignition probability, that means that any evaluation of the total ignited event frequency would account for jet fires as ignited events even if those jet fires did not result in flammable cloud accumulation remote from the leak in the room volume.

5.4.4 Servicing: Reclaiming versus Venting

There was a particular focus on the difference between reclaiming (recovery) and venting R-290 as part of the servicing process. The risks associated with reclamation and venting are similar assuming that all processes are properly followed. A full fault tree analysis evaluating the degree to which procedural steps are properly followed for reclaiming versus venting was beyond the scope of the present project.

The most likely event during either the reclamation process or venting is a jet plume resulting from a leak in the piping that is transferring the refrigerant. If the cabinet is serviced in its original position, there is still a significant likelihood of the jet impinging as assumed for leaks during normal operations (although it would be somewhat less if the condensing unit is open or exposed).

The primary difference between reclamation and venting versus normal operations in terms of accounting for it in the risk model is that the likelihood of human error and/or missing procedural steps. For the risk model, the likelihood of a release during servicing is accounted for by multiplying a factor of 10 to the leak frequency during servicing scenarios.

Reclaiming and venting are not treated separately in the model because depending on the technician's quality of following the procedure, the failure results are similar. For venting, there may be an accidental release into the room via either piping failure or human error. It's also uncertain whether the technician would flush the system with oxygen-free nitrogen. For reclamation, piping or the reclamation machine may leak or fail also leading to an accidental release in the space.

In order to quantify the difference between reclaiming and venting in a detailed fashion, a full fault tree analysis would have to be performed evaluating the degree to which procedural steps are followed. It would also be beneficial to evaluate the steps from a human factors perspective as part of identifying how to better ensure that procedures are easily followed.

5.5 Uncertainty, Assumptions, and Relative Risk

There is a certain degree of uncertainty inherent to risk assessments, and therefore assumptions must be made to fill in the gaps.

Particular to evaluations of leaks in the refrigeration cycle, it is difficult to establish appropriate leak frequencies due to the inconsistent historical data on leaks. Various research has been done on leak causes and their likelihood in various HVAC and refrigeration contexts; however, there is no consistent historical database of leaks because of the wide range of different systems, maintenance records, etc.

The data used in this report from Colbourne et al. [17, 18] is derived from a report published by Parasense in 2000 based on leak detection in UK supermarkets. That single data source has been used in many risk assessments because it is one of the most complete records available for refrigerant leak data. This data is coupled with methods from the oil and gas industry which has a longer history of utilizing historical leak data to perform quantitative risk assessments. There is a lack of properly standardized data sources to establish any region-specific trends or trends that account for the effects of equipment aging and/or maintenance programs on leak frequencies. Because of the uncertainty regarding the leak frequencies (which form the basis of the event frequencies and risk results), the general approach of this report is to focus on relative evaluations of risk. By focusing on relative evaluations of risk, the importance of the leak frequencies when interpreting the results decreases significantly. The primary input from the leak frequencies to evaluating relative risk is the distribution of the likelihood of different hole sizes. From that perspective, the distribution of the hole sizes in the leak frequencies calculated for this study are generally in-line with industry expectations and available data sources.

The term "relative risk" means that evaluations of risk are performed relative to other results performed in this same study to analyze the implications of particular variables. For example, the total ignited event frequency for cabinets with either top-mounted or bottom-mounted condenser units could be compared to determine the relative benefit or drawback to selecting top-mounted or bottom-mounted units. This relative benefit (or drawback) is somewhat insensitive to leak frequency since the same leak frequency data is applied to both calculations. If we were to change the leak frequency data (but preserve the distribution between hole sizes), the results would be the same. So as a result of focusing on relative risk, the primary input from the leak frequencies is the distribution of the likelihood of different hole sizes.

Although the focus is on relative risk to reduce the reliance on the absolute values of the leak frequencies, the uncertainty regarding the leak frequencies does not necessarily mean that the leak frequencies are inaccurate or not representative. However, without sufficient data sources for comparison, it is difficult to establish the quality of the leak frequencies.

In addition to the uncertainty regarding the leak frequencies, a number of assumptions were made in order to complete the study. Assumptions were selected to be conservative to avoid underestimating the risk. As a result, it is expected that the study represents conservatively high risk because of some key assumptions:

- The risk assessment does not account for room ventilation from either room tightness (door gaps, etc.) or mechanical ventilation (HVAC, etc.). Although this does make for a conservative study, it would be more realistic to account for some degree of ventilation since these refrigeration cabinets would never be expected to be used in environments devoid of ventilation. Accounting for ventilation would likely reduce the consequences of some of the smaller (but more frequent) leak rates, especially in kitchens where air change rates are high.
- The risk assessment CFD simulations used diffuse leaks to represent impinging leaks. Diffuse leaks mean minimum momentum and represent the worst-case of possible leaks. This representation is essentially the opposite of high momentum jets that result in homogeneously mixed environments—however, there could be intermediate steps between leaks that result in a homogeneously mixed environment and leaks that have no momentum. The selection of diffuse leaks is intended to be conservative as it represents the worst-case; however, in reality, not all cases would be the worst-case.
- In-cabinet releases are represented in an extremely conservative way.
    - The entire charge is first released into a completely sealed cabinet prior to opening the door
    - When the door is opened, the ignition occurs at the time when the accumulated fuel volume is the largest.
        - Modeling shows that the accumulated fuel volume from these in-cabinet releases quickly disperses within a room, especially when the room footprint is large.
        - Closed display cases likely have some air exchange with the environment even when the doors are closed, and given that most leaks would take on the order of hours to release the entire charge, any small air change rate inside a closed cabinet will significantly reduce the maximum accumulated fuel volume. While we could not find any information on infiltration rates for closed display cases, an experimental study [21] measured air changes rates of 2-12 ACH in domestic refrigerators with magnetic seals.
    - Therefore, the worst-possible in-cabinet release of the whole charge is being used as a representative case for all in-cabinet releases.

- Further, the likelihood of ignition for these cases does not account for the considerably transient nature of the cloud.

- That the ignition model does not account for the transient nature of accumulated fuel volumes during leaks external to display case (in addition to inside as mentioned above). The refrigerant accumulates in the domain over time as it is being released and mixes with air. When the leak has ended, the mixing will continue and the accumulated volume will decrease over time. The current ignition model effectively evaluates the likelihood of ignition at the time of maximum accumulated volume; however, the likelihood of igniting that cloud would be more realistic if dependent on dispersion characteristics of the refrigerant in the geometry over time.
- All leaks are assumed to be at a constant flow rate for the duration of the leak. Although this may be reasonable for liquid leaks at the beginning, it is conservative for vapor leaks where the effect of evaporative cooling would reduce the flow rate. It addition, it does not take depressurization into account, which will also reduce the leak rate and may result in some of the refrigerant remaining inside of the system rather than escaping as the pressure equalizes.
- It is always assumed that the whole charge is leaked. Sources indicate that a portion of the refrigerant would be dissolved in the compressor oil—reducing the total mass released.

5.6 Results

5.6.1 Charge Size and Geometry Assumptions

Figure 5.31 shows the total ignited event frequency for all geometries and charge sizes assuming top-mounted condenser units with the fans on 60% of the time. Table 5.11 shows the same data from the figure as a table. As expected, as the charge size increases so does the ignited event frequency as the mass of R-290 available to accumulate within the space also increases. Also, geometries two and five are kitchens and the risk assessment assumes a higher ignition source density per unit volume than the other geometries. Lastly, the largest geometry (six) has the lowest overall ignition event frequency for each charge size due to increased dilution for any released mass.

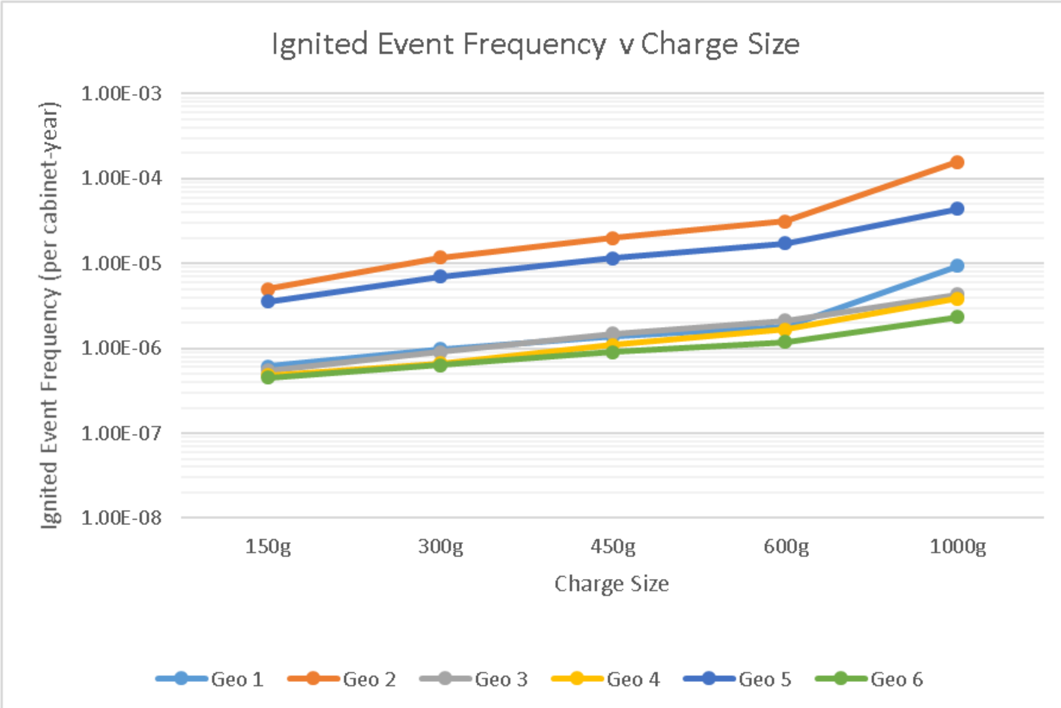


Figure 5.31: Ignited Event Frequencies for All Geometries and Charge Sizes, Top-mounted, 60% fans

Table 5.11: Ignited Event Frequencies for All Geometries and Charge Sizes, Top-mounted, 60% fans

Top-mounted, 60% fans						
	Ignited Event Frequency (per cabinet-year)					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	6.15E-07	4.98E-06	5.53E-07	4.81E-07	3.55E-06	4.53E-07
300g	9.82E-07	1.17E-05	9.04E-07	6.65E-07	6.95E-06	6.34E-07
450g	1.38E-06	2.01E-05	1.49E-06	1.10E-06	1.15E-05	9.02E-07
600g	1.81E-06	3.14E-05	2.13E-06	1.68E-06	1.73E-05	1.19E-06
1000g	9.41E-06	1.56E-04	4.33E-06	3.89E-06	4.41E-05	2.32E-06

Table 5.12 shows the same data reorganized to provide insight into the relative change in total ignited event frequency compared to a 150 g (0.33 lb) charge for each respective geometry. This graph again shows that that as the charge size increases, so does the mass available to accumulate and ignite for a given release.

Table 5.12: Increase in Total Ignited Event Frequencies compared to 150 g (0.33 lb) for Top-mounted, 60% fans

Top, 60% fans versus 150g						
	Factor Increase in Total Ignited Event Frequency					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	--	--	--	--	--	--
300g	1.6x	2.3x	1.6x	1.4x	2.0x	1.4x
450g	2.2x	4.0x	2.7x	2.3x	3.2x	2.0x
600g	2.9x	6.3x	3.9x	3.5x	4.9x	2.6x
1000g	15.3x	31.4x	7.8x	8.1x	12.4x	5.1x

Figure 5.32 shows the total ignited event frequency for all geometries and charge sizes assuming bottom-mounted condenser units with the fans on 60% of the time. Table 5.13 shows the same data in the figure as a table. Similar to the top-mounted cases, as the charge size increases so does the ignited event frequency as the mass available to accumulate within the space also increases. The largest geometry (six) again has the lowest overall ignition event frequency for each charge size (except 150 g (0.33 lb)) due to the increased dilution for any released mass.

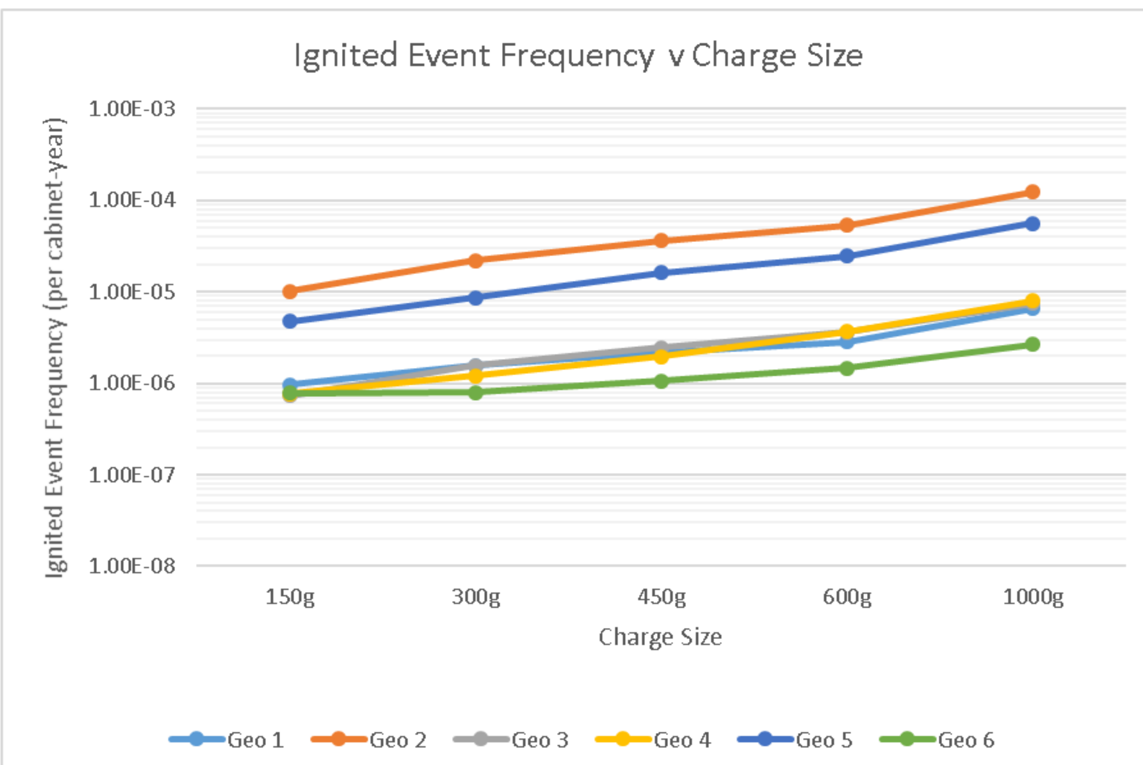


Figure 5.32: Ignited Event Frequencies for All Geometries and Charge Sizes, Bottom-mounted, 60% Fans

Table 5.13: Ignited Event Frequencies for All Geometries and Charge Sizes, Bottom-mounted, 60% Fans

Bottom-mounted, 60% fans						
	Ignited Event Frequency (per cabinet-year)					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	9.63E-07	1.01E-05	7.38E-07	7.70E-07	4.79E-06	7.82E-07
300g	1.57E-06	2.19E-05	1.57E-06	1.20E-06	8.64E-06	7.92E-07
450g	2.18E-06	3.63E-05	2.46E-06	1.98E-06	1.62E-05	1.06E-06
600g	2.85E-06	5.36E-05	3.59E-06	3.70E-06	2.44E-05	1.47E-06
1000g	6.56E-06	1.23E-04	7.51E-06	7.97E-06	5.64E-05	2.68E-06

Servicing generally represented a small contribution to the overall ignited event frequency. Table 5.14 shows the frequencies for servicing events for top-mounted units with 60% fans across all geometries and charge sizes. As discussed in Sections 5.4.3 and 5.4.4, servicing (in particular, the venting or recovery) involves an elevated leak frequency and ignition probability when compared to normal operation; however, because of the small percentage of time that servicing occurs (see Section 5.4.2), the overall contribution to risk is relatively small.

Table 5.14: Ignited Event Frequencies (Recovery / Venting Events) for Top-mounted Units, 60% Fans

Top-mounted, 60% fans, recovery / venting						
	Ignited Event Frequency (per cabinet-year)					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	5.27E-08	6.38E-08	5.21E-08	8.60E-08	5.41E-08	5.19E-08
300g	6.79E-08	1.19E-07	6.68E-08	1.10E-07	4.38E-08	5.90E-08
450g	8.22E-08	1.88E-07	8.29E-08	2.52E-07	6.01E-08	7.08E-08
600g	9.64E-08	2.77E-07	9.96E-08	1.85E-07	8.24E-08	8.26E-08
1000g	4.21E-07	1.94E-06	1.47E-07	1.24E-06	4.14E-07	1.14E-07

The results presented for servicing are meant to represent either recovery (reclaiming) or venting. As discussed in Section 5.4.4, if procedures are followed, the risks associated with either recovery or venting are similar. Therefore, the primary differences between the two approaches would be determined by the degree to which procedures are not followed or human error during the servicing process, which was outside the scope of the present project.

5.6.2 Condensing Unit Location and Fans

Figure 5.33 shows the total ignited event frequency for all geometries and charge sizes assuming top-mounted condenser units with the fans on 100% of the time. Table 5.15 shows the same data from the figure as a table.

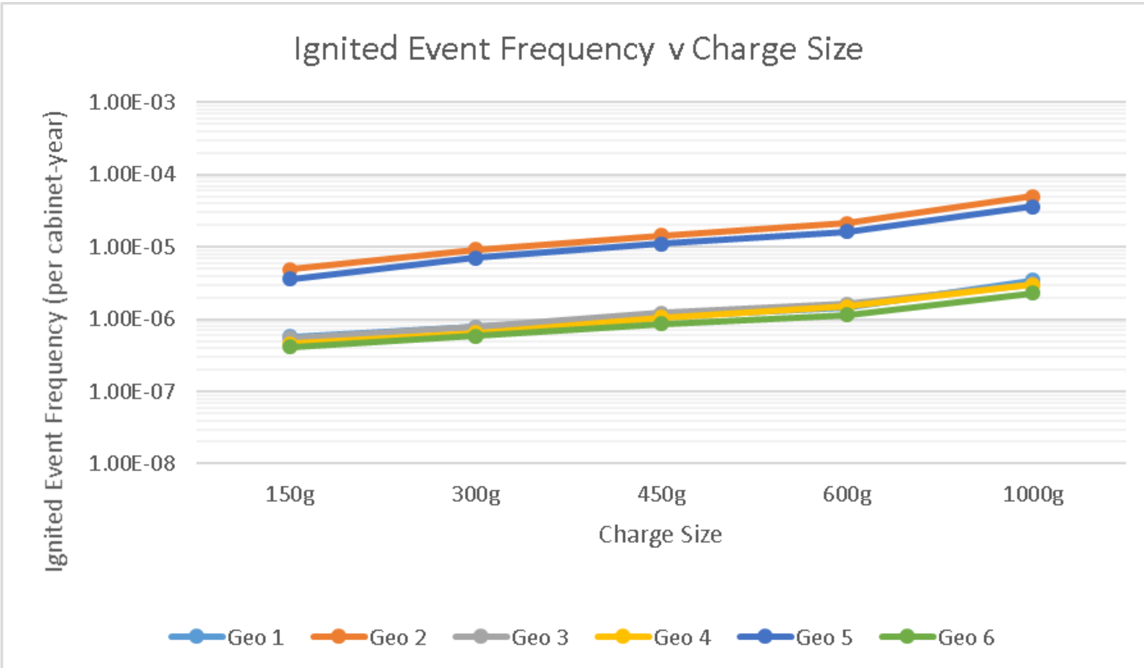


Figure 5.33: Ignited Event Frequencies for All Geometries and Charge Sizes, Top-mounted, 100% Fans

Table 5.15: Ignited Event Frequencies for All Geometries and Charge Sizes, Top-mounted, 100% Fans

Top-mounted, 100% fans						
	Ignited Event Frequency (per cabinet-year)					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	5.79E-07	4.85E-06	5.48E-07	4.56E-07	3.61E-06	4.10E-07
300g	7.82E-07	9.19E-06	7.80E-07	6.45E-07	6.99E-06	5.80E-07
450g	1.11E-06	1.44E-05	1.21E-06	1.06E-06	1.11E-05	8.57E-07
600g	1.48E-06	2.14E-05	1.63E-06	1.48E-06	1.62E-05	1.14E-06
1000g	3.49E-06	5.03E-05	3.04E-06	3.02E-06	3.64E-05	2.28E-06

Figure 5.34 shows the total ignited event frequency for all geometries and charge sizes assuming bottom-mounted condenser units with the fans on 100% of the time. Table 5.16 shows the same data from the figure as a table.

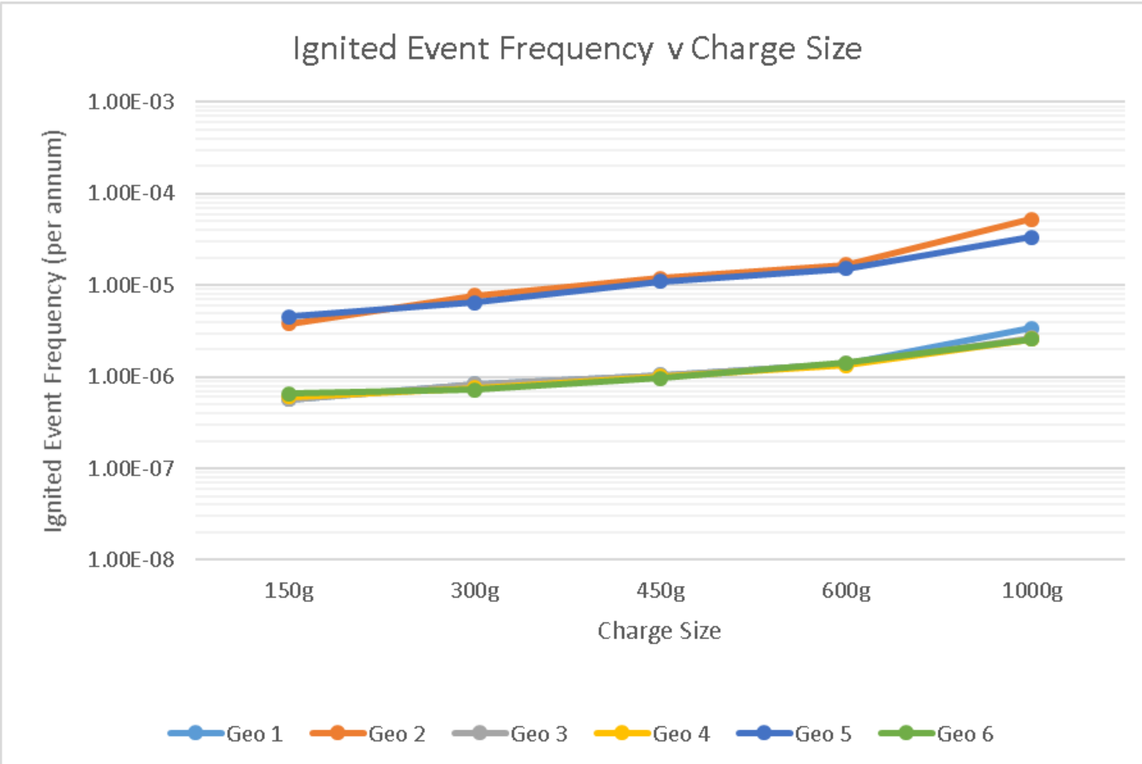


Figure 5.34: Ignited Event Frequencies for All Geometries and Charge Sizes, Bottom-mounted, 100% fans

Table 5.16: Ignited Event Frequencies for All Geometries and Charge Sizes, Bottom-mounted, 100% fans

Bottom-mounted, 100% fans						
	Ignited Event Frequency (per cabinet-year)					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	5.69E-07	3.82E-06	5.65E-07	6.01E-07	4.56E-06	6.51E-07
300g	8.35E-07	7.69E-06	8.31E-07	7.61E-07	6.50E-06	7.16E-07
450g	1.04E-06	1.20E-05	1.05E-06	1.01E-06	1.10E-05	9.62E-07
600g	1.38E-06	1.68E-05	1.40E-06	1.33E-06	1.51E-05	1.41E-06
1000g	3.41E-06	5.28E-05	2.67E-06	2.59E-06	3.37E-05	2.60E-06

The data from the preceding figures and tables can be combined to evaluate the relative change in frequency between changing the variables: bottom-mounted versus top-mounted and fans on 60% versus 100% of the time. Table 5.17 shows the relative change in the ignited event frequency between top and bottom mounted condenser units—i.e. the ratio of bottom-mounted to top-mounted ignited event frequency. A value greater than 1 indicates that the top mounted unit has a lower frequency (shown in green), and a value less than 1 indicates that the bottom mounted unit has a lower frequency (shown in red).

Table 5.17: Relative Comparison of Ignited Event Frequency for Top vs Bottom units, 60% Fans

Bottom vs Top, 60% fans						
	Relative Ignited Event Frequency (Bottom / Top)					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	1.57	2.02	1.33	1.60	1.35	1.73
300g	1.60	1.88	1.73	1.81	1.24	1.25
450g	1.58	1.80	1.65	1.80	1.41	1.17
600g	1.57	1.70	1.68	2.21	1.41	1.23
1000g	0.70	0.79	1.73	2.05	1.28	1.15

Generally speaking, there are reasonable gains in using a top-mounted unit when compared to a bottom-mounted unit. For example, the ignited event frequency is 1.2-2.0 times lower for a top-mounted unit when compared to a bottom-mounted unit.

For the 1000 g (2.2 lb) charge in the smallest geometries, the trend doesn't hold true due to the better mixing being less beneficial; however, 1000 g (2.2 lb) charges should never be used in those size rooms because the cloud would reach LFL if homogeneously mixed (as discussed in Section 2.3 - 2.4).

Table 5.18 shows the relative change in the ignited event frequency between 60% and 100% fans for top-mounted condenser units. Table 5.19 shows the relative change in the ignited event frequency between 60% and 100% fans for bottom-mounted condenser units. A positive value (shown in green) indicates that the ignited release frequency decreased when changing the fan time percentage from 60% to 100%, while a negative value (shown in red) indicates that the frequency increased for the same change.

Table 5.18: Relative Comparison of Ignited Event Frequency for Top-mounted Units, 60% vs 100% Fans

Top, 60% vs 100% fans						
	Relative Ignited Event Frequency (60% Fans / 100% Fans)					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	1.06	1.03	1.01	1.05	0.98	1.10
300g	1.25	1.27	1.16	1.03	0.99	1.09
450g	1.25	1.40	1.23	1.03	1.03	1.05
600g	1.23	1.47	1.30	1.13	1.07	1.04
1000g	2.70	3.11	1.43	1.29	1.21	1.02

Table 5.19: Relative Comparison of Ignited Event Frequency for Bottom-mounted Units, 60% vs 100% Fans

Bottom, 60% vs 100% fans						
	Relative Ignited Event Frequency (60% Fans / 100% Fans)					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	1.69	2.64	1.30	1.28	1.05	1.20
300g	1.88	2.85	1.89	1.58	1.33	1.11
450g	2.09	3.02	2.34	1.96	1.47	1.10
600g	2.07	3.19	2.56	2.77	1.62	1.04
1000g	1.92	2.34	2.82	3.08	1.67	1.03

With the top-mounted condenser units, there is a marginal benefit to running the fans all the time, especially for the larger geometries. This is due to the increased dilution created by the leaking refrigerant falling to the floor, hence there is only minor additional dilution created by the fan air flow. There is somewhat of a benefit in the smaller volumes, even when the charge size is properly sized to say 20-25% of the LFL if mixed in the entire room volume (around 0.0095 kg/m^3 (0.00059 lb/ft^3)).

In contrast, there are reasonable gains to running the fans all the time for bottom-mounted units. For example, the ignited event frequency is up to 3.2 times lower for the fans 100% on when compared 60% operation for bottom-mounted units. As there is limited mixing with air for the bottom-mounted low momentum releases, the increased fan operation can increase the dilution of releases near floor level for bottom-mounted units more so than for top-mounted units.

In fact, the likelihood of ignition becomes very similar for both bottom-mounted and top-mounted units with 100% fan operation as shown in Table 5.20. Although there are some outliers caused by specifics in the geometry, generally the results are similar (near one) for top-mounted and bottom-mounted units provided the fans are always on. In other words, the likelihood of a fire is about the same for top-mounted and bottom-mounted units when the fans are always running.

Table 5.20: Relative Ignited Event Frequency for 100% fans, top-mounted vs bottom-mounted

Bottom vs Top, 100% fans						
	Relative Ignited Event Frequency (Bottom / Top)					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	0.98	0.79	1.03	1.32	1.26	1.59
300g	1.07	0.84	1.07	1.18	0.93	1.23
450g	0.94	0.84	0.87	0.95	0.98	1.12
600g	0.93	0.79	0.86	0.90	0.93	1.23
1000g	0.98	1.05	0.88	0.86	0.93	1.14

There are two main things to consider with these results. The results demonstrate that:

1. When condenser fans are operated normally during the leak, an ignition event in top-mounted units are 1.2-2.0 times less likely than bottom-mounted units
2. When the condenser fan is always on, there is not a significant difference between the total ignited event frequency of cabinets with top-mounted and bottom-mounted condensing units. This is because when the fans are always on, the ignited event frequency is only marginally improved for top-mounted units while the reduction can be up to 3.2 times for bottom-mounted units.

The model is however sensitive to the selection of probability of in-cabinet releases (discussed next). In addition, the metric being evaluated is total ignited event frequency and accounts for all fires as opposed to a particular consequence severity (e.g. 80 TDU or overpressure of 0.1 psi).

5.6.3 In-cabinet Releases

Table 5.21 shows the frequency contribution of in-cabinet leaks when the likelihood of in-cabinet leaks is assumed to be 20% for a top-mounted unit with fans on 60% of the time. Recall that the ignition model is based on the accumulated fuel volume and is therefore dependent on the dispersion results / consequences, meaning there is a frequency impact to the dispersion results.

Table 5.21: Frequency Contribution of In-cabinet Leaks to Top-mounted, 60% fans, 20% In-cabinet Leaks

Top-mounted, 60% fans						
	Frequency Contribution from In-cabinet Leaks					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	41.3%	56.4%	45.9%	53.0%	79.1%	56.0%
300g	42.6%	47.4%	46.2%	63.3%	79.6%	66.0%
450g	44.8%	44.6%	41.5%	61.1%	78.4%	68.6%
600g	47.6%	42.3%	40.5%	56.0%	77.0%	72.3%
1000g	19.6%	20.1%	42.6%	47.8%	71.1%	79.4%

The table draws attention to the relatively high frequency contribution from in-cabinet releases. The in-cabinet leaks generally represent 40-50% of the total ignited event frequency for the smaller geometries assuming a 20% likelihood of in-cabinet releases, and even larger 50-80% of the total ignited event frequency for the larger geometries. This is driven by the generally lower consequences of external leaks in the larger geometries because of the large room volume contributing to dilution of external releases; however, the in-cabinet results are represented with the same conservative severity—resulting in the effective contribution from the in-cabinet releases being higher.

Recall that the ignition model is based on the accumulated fuel volume and is therefore dependent on the dispersion results / consequences—which means there is a frequency impact to the dispersion results. As such, it is relevant that the in-cabinet leaks are represented very conservatively (discussed in Section 5.5) and generally contribute to over 40% of all ignited event frequencies, despite accounting for only 20% of the possible leaks. The effect of the dispersion results on the ignition probability drives the variation between the input value of 20% and the resulting frequency contribution—and that effect makes further discussion of the in-cabinet releases relevant (see Section 5.7.2)

5.6.4 Relative to Consequence Severity

The following set of tables provide frequencies for selected TDU and overpressure consequences for some combinations of charge sizes and geometries for top-mounted units with fans on 60% of the time (refer to Table 3.7 for effects of TDU on the human body). These tables can be used to approach the results of the risk study by selecting a particular degree of consequence severity that the reader may deem appropriate for benchmarking purposes. The highlighted geometries are those that are relevant to the charge size in each table based on standard EN-378. In the tables, values of "--" indicate that the frequency is zero for those cases (based on this risk model).

Table 5.22: Risk Results by Thermal Dose and Overpressure for 150g charge, top-mounted unit, 60% fans

150g Charge, Top-mounted, 60% fans						
	Ignited Event Frequency for Selected Consequence					
Thermal Dose (tdu)	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
0	6.15E-07	4.98E-06	5.53E-07	4.81E-07	3.55E-06	4.53E-07
80	3.85E-07	4.09E-06	3.41E-07	2.90E-07	2.86E-06	2.68E-07
130	3.27E-07	2.98E-06	2.69E-07	2.60E-07	2.81E-06	2.68E-07
240	--	--	--	--	--	--
350	--	--	--	--	--	--
500	--	--	--	--	--	--

150g Charge, Top-mounted, 60% fans						
	Ignited Event Frequency for Selected Consequence					
Overpressure (psi)	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
0	6.15E-07	4.98E-06	5.53E-07	4.81E-07	3.55E-06	4.53E-07
1.0	4.98E-07	4.72E-06	--	--	--	--
2.0	1.09E-07	1.02E-06	--	--	--	--
3.0	--	--	--	--	--	--
5.0	--	--	--	--	--	--

Table 5.23: Risk Results by Thermal Dose and Overpressure for 300g charge, top-mounted unit, 60% fans

300g Charge, Top-mounted, 60% fans						
	Ignited Event Frequency for Selected Consequence					
Thermal Dose (tdu)	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
0	9.82E-07	1.17E-05	9.04E-07	6.65E-07	6.95E-06	6.34E-07
80	8.66E-07	1.14E-05	7.90E-07	4.84E-07	6.64E-06	4.40E-07
130	8.66E-07	1.14E-05	6.79E-07	4.70E-07	5.94E-06	4.29E-07
240	6.39E-07	9.07E-06	4.93E-07	4.50E-07	5.53E-06	4.23E-07
350	--	--	--	--	--	--
500	--	--	--	--	--	--

300g Charge, Top-mounted, 60% fans						
	Ignited Event Frequency for Selected Consequence					
Overpressure (psi)	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
0	9.82E-07	1.17E-05	9.04E-07	6.65E-07	6.95E-06	6.34E-07
1.0	4.43E-07	5.92E-06	2.59E-07	3.18E-08	--	--
2.0	4.42E-07	5.92E-06	2.02E-08	--	--	--
3.0	4.40E-07	4.00E-06	--	--	--	--
5.0	8.67E-08	1.91E-06	--	--	--	--

Table 5.24: Risk Results by Thermal Dose and Overpressure for 450g charge, top-mounted unit, 60% fans

450g Charge, Top-mounted, 60% fans						
	Ignited Event Frequency for Selected Consequence					
Thermal Dose (tdu)	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
0	1.38E-06	2.01E-05	1.49E-06	1.10E-06	1.15E-05	9.02E-07
80	1.24E-06	1.99E-05	1.28E-06	8.99E-07	1.07E-05	6.49E-07
130	1.24E-06	1.94E-05	1.28E-06	7.92E-07	1.06E-05	6.36E-07
240	1.21E-06	1.94E-05	1.26E-06	7.11E-07	9.73E-06	6.36E-07
350	9.41E-07	1.51E-05	8.47E-07	6.70E-07	9.04E-06	6.23E-07
500	9.59E-09	1.66E-07	--	1.49E-08	--	--

450g Charge, Top-mounted, 60% fans						
	Ignited Event Frequency for Selected Consequence					
Overpressure (psi)	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
0	1.38E-06	2.01E-05	1.49E-06	1.10E-06	1.15E-05	9.02E-07
1.0	1.24E-06	1.99E-05	6.63E-07	1.15E-07	--	--
2.0	6.16E-07	1.09E-05	6.38E-07	5.14E-08	--	--
3.0	6.16E-07	1.04E-05	2.15E-07	--	--	--
5.0	5.56E-07	1.04E-05	--	--	--	--

Table 5.25: Risk Results by Thermal Dose and Overpressure for 600g charge, top-mounted unit, 60% fans

600g Charge, Top-mounted, 60% fans						
	Ignited Event Frequency for Selected Consequence					
Thermal Dose (tdu)	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
0	1.81E-06	3.14E-05	2.13E-06	1.68E-06	1.73E-05	1.19E-06
80	1.65E-06	3.13E-05	1.90E-06	1.43E-06	1.67E-05	8.83E-07
130	1.65E-06	3.13E-05	1.90E-06	1.40E-06	1.59E-05	8.83E-07
240	1.61E-06	3.13E-05	1.90E-06	1.40E-06	1.53E-05	8.83E-07
350	1.31E-06	2.90E-05	1.86E-06	1.25E-06	1.46E-05	8.70E-07
500	1.11E-06	2.16E-05	1.13E-06	1.00E-06	1.37E-05	8.70E-07

600g Charge, Top-mounted, 60% fans						
	Ignited Event Frequency for Selected Consequence					
Overpressure (psi)	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
0	1.81E-06	3.14E-05	2.13E-06	1.68E-06	1.73E-05	1.19E-06
1.0	1.66E-06	3.13E-05	1.04E-06	5.39E-07	1.28E-06	--
2.0	7.87E-07	1.80E-05	1.03E-06	4.25E-07	--	--
3.0	7.47E-07	1.79E-05	9.96E-07	1.30E-07	--	--
5.0	7.03E-07	1.79E-05	--	--	--	--

Table 5.26: Risk Results by Thermal Dose and Overpressure for 1000g charge, top-mounted unit, 60% fans

1000g Charge, Top-mounted, 60% fans						
	Ignited Event Frequency for Selected Consequence					
Thermal Dose (tdu)	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
0	9.41E-06	1.56E-04	4.33E-06	3.89E-06	4.41E-05	2.32E-06
80	9.09E-06	1.56E-04	4.10E-06	3.67E-06	4.27E-05	1.90E-06
130	9.09E-06	1.56E-04	4.10E-06	3.64E-06	4.27E-05	1.90E-06
240	9.09E-06	1.56E-04	4.10E-06	3.59E-06	4.21E-05	1.86E-06
350	9.09E-06	1.56E-04	4.05E-06	3.59E-06	4.21E-05	1.86E-06
500	9.09E-06	1.54E-04	3.94E-06	2.98E-06	4.21E-05	1.86E-06

1000g Charge, Top-mounted, 60% fans						
	Ignited Event Frequency for Selected Consequence					
Overpressure (psi)	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
0	9.41E-06	1.56E-04	4.33E-06	3.89E-06	4.41E-05	2.32E-06
1.0	9.10E-06	1.56E-04	2.63E-06	2.16E-06	1.74E-05	--
2.0	9.09E-06	1.31E-04	2.63E-06	2.12E-06	5.31E-06	--
3.0	7.60E-06	1.31E-04	2.58E-06	1.50E-06	--	--
5.0	7.54E-06	1.31E-04	2.45E-06	8.41E-07	--	--

5.6.5 Context

To put the risk results in context, the range of ignited event frequencies were on the order of 10^{-6} to 10^{-7}, except for the large kitchen (geometry 5) whose ignited event frequencies were an order of magnitude larger (10^{-5} to 10^{-6}). These frequencies represent all possible fire events—including those that would result in no harm. An interesting comparison is that the average annual frequency of being involved in a motor vehicle accident reported to the police is on the order of 10^{-6} per mile based on 2015 NHTSA statistics.

Other frequency statistics can be used to get a sense of what these frequencies mean in context. The frequency of a person getting injured due to a slip, trip, or fall is on the order of 10^{-2} whereas the likelihood of building fires originating from televisions is on the order of 10^{-5}.

The table below includes a few additional examples from various sources.

Hazard	**Risk per Person or Building per Year**	**Source**
Slip/fall injury requiring medical treatment	3E-02	CDC via Gradient [19]
Commercial building fire significant enough to warrant fire department response	2E-02	NFDC via Gradient [19]
Commercial building fire resulting from cooking activity	3E-03	NFDC via Gradient [19]
Fatal injury at work (all occupations)	4E-05	NSC via Gradient [19]
Injury at work due to fires or explosions	8E-06	NSC via Gradient [19]
Fires due to washing machines (UK)	1.3E-05	Waterson via Colbourne [17]
Fires due to televisions (UK)	2.7E-05	Waterson via Colbourne [17]

5.7 Discussion

In the absence of particular risk acceptance criteria (i.e. a frequency for a particular consequence—e.g. 150 TDU at a frequency of $1x10^{-6}$), the results are presented in such a way as to provide insight into the risk of various charge sizes relative to what is currently acceptable. As such, it was decided to benchmark the frequency of any fire event (ignited event frequency) relative to a particular scenario evaluated in the risk study that would be acceptable under current regulations.

5.7.1 Charge Size, Condensing Unit Location and Fan Operation

For the purposes of drawing conclusions on the risk of differing charge sizes, the scenario of a bottom-mounted 150 g cabinet with fans on 60% of the time in the small kitchen (geometry two) was selected as the basis for benchmarking. This benchmarking scenario represents a scenario that would be acceptable by current regulations.

Table 5.27 shows the relative change in total ignited event frequency for top-mounted units with fans on 60% of the time for all charge sizes and geometries compared to our benchmarking scenario. Table 5.28 shows the similar results for the bottom-mounted units. The values in the table represent the factor by which the ignited event frequency would need to be multiplied to reach the level of the benchmarking scenario. As such, values between 0 and 1 mean that the ignited event frequency is reduced when compared to the original scenario. Values greater than 1 mean that the ignited event frequency is greater than that of the original scenario. For example, a value of "0.5x" means that the frequency is half that of the benchmarking scenario. The green entries in the table represent values for which the charge size is less than 25% of the LFL when homogeneously mixed in the room volume and the frequency of an ignition event is less than that of the benchmarking scenario. The white (non-shaded) entries in the table are those for which the frequency is less than that of the benchmarking scenario but the charge size would be more than 20-25% of the LFL when homogeneously mixed in the room volume. The red entries in the table are those for which the total ignited event frequency is greater than the benchmarking scenario.

Table 5.27: Relative Change in Total Ignited Event Frequency for Top 60% vs Geo 2, bottom, 150g, 60%

Top, 60% fans versus Geo 2, Bottom, 150g, 60% fans						
	Relative Change in Total Ignited Event Frequency					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	0.1x	0.5x	0.1x	0.0x	0.4x	0.0x
300g	0.1x	1.2x	0.1x	0.1x	0.7x	0.1x
450g	0.1x	2.0x	0.1x	0.1x	1.1x	0.1x
600g	0.2x	3.1x	0.2x	0.2x	1.7x	0.1x
1000g	0.9x	15.5x	0.4x	0.4x	4.4x	0.2x

Table 5.28: Relative Change in Total Ignited Event Frequency for Bottom 60% vs Geo 2, bottom, 150g, 60%

Bottom, 60% fans versus Geo 2, Bottom, 150g, 60% fans						
	Relative Change in Total Ignited Event Frequency					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	0.1x	--	0.1x	0.1x	0.5x	0.1x
300g	0.2x	2.2x	0.2x	0.1x	0.9x	0.1x
450g	0.2x	3.6x	0.2x	0.2x	1.6x	0.1x
600g	0.3x	5.3x	0.4x	0.4x	2.4x	0.1x
1000g	0.7x	12.3x	0.7x	0.8x	5.6x	0.3x

The general trend is that the total ignited event frequency of larger charge sizes is not higher than the benchmarking scenario (which is allowed by current EPA regulations) provided that the charge size is also limited by the room volume. The medium kitchen (geometry five) stands out in this regard in that the kitchen is large enough from a volume perspective to have charge sizes of up to 1000 g with the homogeneously mixed concentration not exceeding 20-25% of the LFL. However, there are various conservative assumptions of this study (discussed in Section 5.5) that if modified or evaluated differently might change that result.

Table 5.29 shows the relative change in total ignited event frequency for top-mounted units with fans on 100% of the time for all charge sizes and geometries compared to our benchmarking scenario. Table 5.30 shows similar results for bottom-mounted units. The green entries in the table represent values for which the charge size is less than 25% of the LFL when homogeneously mixed in the room volume and the frequency is less than that of the benchmarking scenario. The white (non-shaded) entries in the table are those for which the frequency is less than that of the benchmarking scenario but the charge size would be more than 25% of the LFL when homogeneously mixed in the room volume. The red entries in the table are those for which the total ignited event frequency is greater than the benchmarking scenario.

Table 5.29: Relative Change in Total Ignited Event Frequency for Top 100% vs Geo 2, bottom, 150g, 60%

Top, 100% fans versus Geo 2, Bottom, 150g, 60% fans						
	Relative Change in Total Ignited Event Frequency					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	0.1x	0.5x	0.1x	0.0x	0.4x	0.0x
300g	0.1x	0.9x	0.1x	0.1x	0.7x	0.1x
450g	0.1x	1.4x	0.1x	0.1x	1.1x	0.1x
600g	0.1x	2.1x	0.2x	0.1x	1.6x	0.1x
1000g	0.3x	5.0x	0.3x	0.3x	3.6x	0.2x

Table 5.30: Relative Change in Total Ignited Event Frequency for Bottom 100% vs Geo 2, bottom, 150g, 60%

Bottom, 100% fans versus Geo 2, Bottom, 150g, 60% fans						
	Relative Change in Total Ignited Event Frequency					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
Charge Size	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
150g	0.1x	0.4x	0.1x	0.1x	0.5x	0.1x
300g	0.1x	0.8x	0.1x	0.1x	0.6x	0.1x
450g	0.1x	1.2x	0.1x	0.1x	1.1x	0.1x
600g	0.1x	1.7x	0.1x	0.1x	1.5x	0.1x
1000g	0.3x	5.2x	0.3x	0.3x	3.3x	0.3x

When changing the fans to always be on, there is some improvement to the results (as discussed earlier); however, the general trend with respect to risk of various charge sizes is about the same. One area of note is whether a 300g charge can be used in the small kitchen (geometry two). Technically the charge size is just above the 20-25% LFL constraint which limits the charge size to 238-297g; however, when the fans are on 100% of the time, the total ignited event frequency has dropped enough to fall under that of the benchmarking scenario.

All of the results discussed so far are based on the input parameters described in Section 5.4.2. The primary prevention and mitigation measures evaluated as part of the risk assessment are the location of the condensing unit (top-mounted or bottom-mounted) and the fan time percentage (fans on with compressor or always on). Neither of these measures affect one of the critical input parameters—the likelihood of in-cabinet releases / the distribution between in-cabinet and outside releases.

5.7.2 Contribution of In-cabinet Releases

Table 5.31 shows the total ignited event frequency for geometry one with a 150 g charge size when varying the fan time percentage and the likelihood of in-cabinet leaks.

Table 5.31: Ignited Event Frequency Sensitivity - Fan Time vs In-cabinet Leaks

Ignited Event Frequency - Geometry 1, 150g				
Fan Time Percentage	**Likelihood of In-cabinet Leak**			
	0%		**80%**	
	Top	**Bottom**	**Top**	**Bottom**
0%	5.06E-07	1.59E-06	1.16E-06	1.44E-06
60%	4.38E-07	8.52E-07	1.15E-06	1.30E-06
100%	3.94E-07	3.59E-07	1.14E-06	1.20E-06

As would be expected, when 80% of the leaks are inside the cabinet, the effect of varying the fan time percentage is minimal because the fans do not affect the in-cabinet leaks. Conversely, if in-cabinet leaks could be eliminated, the fans have a much more pronounced impact, especially for leaks from bottom-mounted condenser units. This again is due to the increased dilution created by the leaking refrigerant falling to the floor from top-mounted units, hence there is only minor additional dilution created by the fan air flow while bottom-mounted units do not mix readily with the air as the release spreads along the ground. As such, if only focused on external leaks, fans are an effective mitigation measure, especially for bottom-mounted units.

However, as described in Section 5.6.3, while only 20% of the releases occur within the display cabinet, the in-cabinet leaks generally represent more than 40% of the total ignited event frequency. This disproportionate fraction of the ignition events occurring from in-cabinet leaks is based on conservative assumptions discussed in Section 5.5.

Table 5.32 shows the total ignited event frequency for all geometries for a top-mounted unit with 150 g charge and 60% fan time percentage varying the likelihood of in-cabinet leaks. The table is meant to provide insight into the potential benefits of risk reduction measures aimed at in-cabinet releases.

Table 5.32: Sensitivity of Ignited Event Frequency to Likelihood of In-cabinet Leaks, 150g, Top, 60% fans

Top-mounted, 60% fans, 150g charge						
Probability of In-cabinet Leaks	Ignited Event Frequency					
	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
0%	4.38E-07	2.70E-06	3.61E-07	2.70E-07	9.14E-07	2.36E-07
5%	4.83E-07	3.27E-06	4.09E-07	3.23E-07	1.57E-06	2.90E-07
10%	5.27E-07	3.84E-06	4.57E-07	3.76E-07	2.23E-06	3.45E-07
20%	6.15E-07	4.98E-06	5.53E-07	4.81E-07	3.55E-06	4.53E-07
40%	7.92E-07	7.26E-06	7.45E-07	6.91E-07	6.19E-06	6.70E-07
80%	1.15E-06	1.18E-05	1.13E-06	1.11E-06	1.15E-05	1.10E-06
100%	1.32E-06	1.41E-05	1.32E-06	1.32E-06	1.41E-05	1.32E-06

Relative Difference in Total Frequency compared to 20%						
Probability of In-cabinet Leaks	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
0%	0.71x	0.54x	0.65x	0.56x	0.26x	0.52x
5%	0.78x	0.66x	0.74x	0.67x	0.44x	0.64x
10%	0.86x	0.77x	0.83x	0.78x	0.63x	0.76x
20%	--	--	--	--	--	--
40%	1.29x	1.46x	1.35x	1.44x	1.74x	1.48x
80%	1.86x	2.37x	2.04x	2.31x	3.23x	2.44x
100%	2.15x	2.83x	2.39x	2.75x	3.97x	2.92x

Table 5.33 presents similar data but for a 1000g charge size.

Table 5.33: Sensitivity of Ignited Event Frequency to Likelihood of In-cabinet Leaks, 150g, Top, 60% fans

Top-mounted, 60% fans, 1000g charge						
	Ignited Event Frequency					
Probability of	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
In-cabinet Leaks	Conv.	S Kitchen	Deli	Market	M Kitchen	Big Box
0%	9.35E-06	1.56E-04	3.07E-06	2.52E-06	1.58E-05	5.71E-07
5%	9.36E-06	1.56E-04	3.39E-06	2.86E-06	2.29E-05	1.01E-06
10%	9.38E-06	1.56E-04	3.70E-06	3.20E-06	3.00E-05	1.45E-06
20%	9.41E-06	1.56E-04	4.33E-06	3.89E-06	4.41E-05	2.32E-06
40%	9.46E-06	1.57E-04	5.59E-06	5.25E-06	7.25E-05	4.08E-06
80%	9.58E-06	1.58E-04	8.11E-06	7.99E-06	1.29E-04	7.58E-06
100%	9.64E-06	1.59E-04	9.37E-06	9.36E-06	1.57E-04	9.33E-06

Relative Difference in Total Frequency compared to 20%						
Probability of						
In-cabinet Leaks	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5	Geo 6
0%	0.99x	1.00x	0.71x	0.65x	0.36x	0.25x
5%	1.00x	1.00x	0.78x	0.74x	0.52x	0.43x
10%	1.00x	1.00x	0.85x	0.82x	0.68x	0.62x
20%	--	--	--	--	--	--
40%	1.01x	1.00x	1.29x	1.35x	1.64x	1.75x
80%	1.02x	1.01x	1.87x	2.06x	2.92x	3.26x
100%	1.02x	1.02x	2.16x	2.41x	3.57x	4.02x

When the comparison is made for the 1000 g charge, one of the first things to notice is that the two smallest geometries are not sensitive to this variable because the consequences of the external releases catch up to the consequences of the in-cabinet releases. This is aligned with that 1000 g is too much charge for the room size regardless of the details of the release mechanism. When looking at a geometry more appropriately sized for the charge size, e.g. geometry six (the big box grocery store), there is a 75% reduction in the ignited event frequency when changing the in-cabinet leak percentage from 20% to 0%. The purpose of the example is to demonstrate the sensitivity of the model to in-cabinet leaks and that mitigating in-cabinet leaks (and accounting for that in the risk model) would result in a sizable effect on the overall risk. The example also demonstrates that in-cabinet leaks are a significant risk driver for very large rooms since external leaks can more readily disperse and mix below the LFL.

5.7.3 Conservatism

As discussed in Section 5.5, the complexity of the study necessitated making conservative assumptions. Consequently, it is expected that the risk results in this study are conservatively higher, mostly because:

- All geometries were assumed to be air-tight (i.e. no ventilation due to doors, windows, or other passive ventilation) with no HVAC or mechanical ventilation
- All impinging leaks were represented as diffuse leaks (having near-zero momentum)
- In-cabinet releases were always represented by the worst-case of releasing the entire charge into a completely sealed cabinet prior to opening the door and taking the cloud characteristics at the point in time for which the accumulated fuel volume is maximized
- Ignition likelihood is based on the peak accumulated fuel volume without accounting for how quickly the volumes mix with air and dissipate.
- All leaks resulted in the entire charge being leaked
- All leaks were assumed to be at a constant flow rate (leak rates did not include effects of depressurization and/or evaporative cooling)

6 Summary and Recommendations

6.1 Main Findings from the Risk Study

- As charge size increases, the frequency of an ignition event increases since the mass of R-290 available to accumulate within the space also increases.
- Servicing generally represents a small contribution to the overall ignited event frequency assuming that the refrigerant is either recovered or vented prior to servicing and that proper procedures are followed.
- The ignited event frequency is 1.2-2.0 times lower when condensing units are top-mounted compared to bottom-mounted.
- There is only a marginal benefit to running the condensing unit fan all the time when the condensing unit is top-mounted.
- It is more beneficial to run the condensing unit fan all the time for bottom-mounted units. For example, the ignited event frequency is up to 3.2 times lower for the fans 100% on compared to 60% on for bottom-mounted units.
- The likelihood of fire events becomes similar for bottom-mounted and top-mounted units when the condensing unit fan is operated continuously.
- Current regulations allow the use of 150 g charge sizes in retail environments, which includes small kitchens. As the surface area of the commercial space increased, the study showed it was possible to scale up to larger charge sizes while maintaining the total ignited event frequency equivalent to or less than that obtained for small kitchens using 150 g charges. The scaling was somewhat inhibited for larger kitchens due to the high density of ignition sources.
- In-cabinet releases represent a large portion of the risk for closed display cases in large rooms.

6.2 Leaks

Loss of containment - external leaks

R-290 leaks from a closed-loop vapor compression cycle will almost always initially have high velocity and momentum due to the high pressures within the system. The velocity from the jet will remain sufficiently high to entrain air into the refrigerant jet, enhancing mixing with air and increasing dilution. If the charge is sized properly relative the room, and a free jet release occurs, the concentration of R-290 homogeneously mixed within the entire room volume will remain below flammable levels. In contrast, if a jet impinges on a nearby surface or obstruction, the velocity and momentum of the jet will be significantly reduced. For example, when leaks occur inside the condenser unit housing, the released jet can impinge on nearby surfaces or on the housing walls thus reducing the momentum of the release. These low momentum leaks will have only limited mixing with air and can result in R-290 accumulation above the LFL in volumes remote from the leak, particularly along the floor.

Condensing unit location – external leaks

The results of the current study show that risk from leaks external to refrigerated display cases in the vicinity of the condensing unit are dominated by "low momentum" releases, which occur when high pressure releases impinge on a surface in the vicinity of the release. Low momentum releases result in reduced mixing with air and the accumulation of refrigerant fuel layers in the space where the display case is installed. Low momentum leaks from bottom-mounted condensers can create fuel-rich layers that spread across the floor, whereas such leaks from top-mounted condensers tend to mix slightly more with air as the released fluid falls to the ground, which results in accumulated fuel layers being taller and having lower fuel concentrations. When the leak rate is small, and there is no external ventilation, releases from bottom-mounted condensing units can still form fuel-rich layers whereas releases from top-mounted condensing units will generally dilute below flammable levels. In contrast, free jet releases have enough momentum to homogeneously mix the released refrigerant with air, thus diluting concentrations below flammable levels if the room is sized properly.

The results demonstrate that under normal operation (compressor/condensing unit fan in operation 60% of the time), the likelihood of having an ignition event with a display case having a bottom-mounted condensing unit is 1.2-2.0 times higher than one with a top-mounted condensing unit. When condensing units are top-mounted, components of the refrigeration circuit are located higher up from the floor. Therefore, external leaks will typically occur higher up which is beneficial in terms of facilitating mixing and reducing the accumulated fuel volumes, especially for the smaller, more frequent leaks.

The results further show that when the condensing unit fan is continuously operated, external low momentum leaks are less likely to result in accumulated fuel volumes in the space where a display case is located. Fan operation provides additional mixing and helps dilute the refrigerant concentrations to below flammable levels for leaks at both top- and bottom-mounted condensing units. Since there is very limited mixing from low momentum leaks at a bottom-mounted condensing unit, the dilution effect from the fan is especially notable. In fact, if the condenser fan is in constant operation there is essentially no difference in the likelihood of an ignition event for display cases with top- or bottom-mounted condensing units.

Internal leaks

Refrigerant charges are sized for the required cooling of the display case and will scale with the size of the display case. In most cases, if the entire charge is released into a closed display case the resulting concentrations will be right near the upper limit of flammability for R-290. Hence, the type of release (jet or low momentum) or whether the evaporator fan is in operation will have little effect on the resulting accumulated volume of refrigerant in the display case. In addition, this further confirms that all equipment within the cabinet should be rated for explosive atmospheres (explosion proof or Ex proof). For open refrigerated display cases (not evaluated in the present study), this will not be the case and internal releases will be more like external leaks.

Under ideal conditions where there is no external air infiltration into a closed display case, the resulting accumulated fuel volume is only dependent on the charge size and volume of the display case. In addition, the current analysis shows that the risk associated with the use of R-290 in closed display cases can be very sensitive to internal releases due to their potentially severe consequences. For example, the likelihood of an ignition event is reduced by a factor of 4 if the current assumption that 20% of all leaks occur within the display case is reduced to 0%. This however is largely due to the assumptions resulting in conservatively larger risk, namely that the probability and severity of an ignition event are based on the maximum accumulated fuel volume and do not account for the transient nature of the release. For example, a 12 g/min external bottom release will take approximately 50 minutes to release 600 g of R-290 charge and result in a similar accumulated mass as a release in the cabinet, which, when suddenly released as the door is open, remains only for 10-20 seconds before diluting.

6.3 Preliminary Recommendations to Reduce Risks

One way of reducing risk is to reduce the likelihood of having a release altogether. While this aspect is beyond the scope of the present study, one recommendation may include continuing the practice of joining components in the refrigeration circuit using brazed connections to reduce the likelihood of leaks and improve the quality of brazed connections.

Methods of Reducing Risk of External Leaks

<u>*Condensing unit fan operation*</u>

It is recommended to operate the condensing unit fan continuously or near continuously to reduce the likelihood of external low momentum leaks resulting in accumulated fuel volume in the space where the display case is located. As the fan provides additional mixing and dilution, it is recommended that it be operational at a minimum during the leak itself. Therefore, if it is not possible to keep the condensing unit fan continuously operational, an alternate design would be to activate the fan on leak detection. The effectiveness of such systems should be thoroughly tested with advanced CFD or experimental studies.

Another possible mitigation measure that was outside scope of the present study, would be the use mechanical ventilation in the commercial space to help dilute any external release of R-290. For example, installations may require that the use of such a unit requires a minimum level of air-changes-per hour within the space or upon confirmed gas detection, mechanical ventilation is activated.

Condensing unit location

The risk assessment has shown that top-mounted condenser location results in reduced ignited event frequencies due to the mixing benefit of the height of the condenser. Assuming the fans are always running, there is not a significant difference between the results for top and bottom-mounted condensing unit locations; however, the top-mounted condensing unit location should be preferred. The reason for this is that the selection of condensing unit location is a passive safety measure that in and of itself cannot fail. Although fan failure rates are relatively low, a fan failure would result in the loss of a critical safety measure, and the failed fan may act as a potential ignition source.

By selecting top-mounted condensing unit location when possible, it acts as a passive safety measure on its own.

Maximum charge size

Charge size limits should be based on display case design and the size of the room where the display case is to be located. Important equipment design aspects include whether the condensing unit is bottom- or top-mounted and whether the condenser fan (if equipped) is set to continuously operate or operate upon leak detection. Units without fans might require smaller maximum charge sizes without demonstrating that sufficient mixing occurs—which may require further design changes and testing.

Smaller charge sizes should be used if fan operation is not continuous. If the condensing unit fan can be continuously operated, then both top-mounted and bottom-mounted units can be designed with larger charges, yet should be limited by some threshold value of the LFL (e.g., 20-25% LFL).

Methods of Reducing Risk of Internal Leaks

The potential consequences of a leak inside a closed display case are independent of condensing unit location and condenser fan operation. In both open and closed display cases, use only equipment components rated for explosive environments (e.g., ATEX or NEC explosion certified) to reduce the likelihood of ignition. Use equipment components rated for hazardous locations involving flammable gas in accordance with nationally recognized standards.

Based on equipment specifications provided by the technical panel, a leak of the entire charge that mixes homogenously inside a closed cabinet results in R-290 concentrations near the UFL. One method to reduce the risk is to ensure that the accumulated fuel volume is diluted prior to the door being opened. This could possibly be accomplished by passive or active mitigation methods. One possible passive method is to design passive venting near the base of the cabinet that provides a low air change rate within the cabinet, which could help dilute refrigerant levels especially for smaller leaks that are more likely.

A possible active method would be to install a leak detection mechanism, and upon confirmed leak detection, activate an extraction fan that exhaust the contents within the cabinet into the room where the display case is located. Ideally, the contents should be vented out of the conditioned space upward to ensure maximum mixing and dilution in the room. This can reduce the likelihood and severity of ignition events inside the cabinet and when a closed display case cabinet is opened after an internal leak has occurred. The possibility of locking the cabinet doors and shutting down all electronics upon confirmed leak detection could also be explored. However, these and additional possible mitigation mechanisms are a topic for further study.

7 Future Work

The present risk results are conservative because we assume: (1) rooms are completely sealed with no infiltration; (2) no mechanical ventilation; (3) the leak rate remains constant at the maximum initial value and does not decrease due to depressurization or evaporative cooling within the system; (4) the entire charge is released during the event; and (5) ignition occurs after the entire charge has been released at the time when the cloud size is maximized. Under these assumptions, flammable volumes can form from small leaks that would otherwise dissipate and disperse if there were additional mixing due to room ventilation. This is particularly true in commercial kitchens as they generally have high air change rates (suggested sufficient ventilation is 20-40 ACH in ref. [22]). In addition, the resulting accumulated fuel volumes will be larger due to the constant leak rates that do not diminish with time.

Follow-on work could include establishing realistic air change rates for the commercial environments of interest and incorporating them into CFD simulations to see the influence on accumulated fuel volumes from low momentum releases. The CFD model used in the present study can simulate refrigerant leaks while also simulating room infiltration. In addition, if room ventilation cannot be guaranteed, an installation may require that confirmed gas detection automatically activates mechanical ventilation within the volume. Future work may be to ensure this approach is most effective, by thoroughly testing gas detection systems with advanced CFD or through experimentation. There are several important design aspects that can be evaluated with these methods, such as optimized sensor placement, activation thresholds, and timing of activated mitigation methods. Additional work should also aim to evaluate the effect of proximity to ignition sources in scenarios that include realistic ventilation.

The risk study has shown that the consequences of an external leak are lower when the condensing unit fan is on during the leak. A way to accomplish this would be to ensure the condensing unit fan remains in operation or to detect leaks and activate the fans upon detection of a leak. Similar to mechanical ventilation, in order for this approach to be most effective, leak detection systems should be thoroughly tested with advanced CFD or through experimentation. There are several important design aspects that can be evaluated with these methods including optimized sensor placement, activation thresholds, and timing of activated mitigation methods.

Another area of future work could be to reduce the conservativeness of how the consequences of in-cabinet releases are modeled. As discussed above, conservative accumulated fuel volumes are likely considered in the present study as all closed display cases are assumed to be air tight, hence the same accumulated cloud regardless of the leak rate. This assumption means that a 0.1 g/min leak will have the same consequences as a 100 g/min release and will not hold true when there is some air exchange rate with the environment, which reduces the size of the accumulated fuel volume, especially for small leak rates. As mentioned previously, air infiltration rates for magnetically sealed domestic refrigerators have been experimentally determined in other studies. The conservatism in ignited consequences for in-cabinet leaks can be further reduced by accounting for the considerably fast transient decay in accumulated fuel volume after the cabinet door is opened. In the current model, it is assumed the that the maximum accumulated fuel volume is always ignited. Incorporating a time dependent ignition model would also likely reduce the degree of conservativism of the risk model for external leaks.

Follow-on work should also include dispersion experiments with leaks from an operating and idle refrigerant compression cycle. This would help establish transient leak rates both in the vapor and liquid segments of the cycle for a range of cooling capacity units (i.e., with varying charge sizes). Tests could be performed to not only quantify the transient leak while in operation and while idle, but also to evaluate the influence transient leak rates have on the outcome of a leak and subsequent consequences.

The risk assessment assumed all impinged releases had essentially no momentum. Depending on several details, such as how far from the leak a release impinges on a surface, leaks can have different reduced momentums compared to a free jet. Real releases could be modeled or examined through experimentation to establish a probability for more intermediate levels of leak momentum than considered in the present study.

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Appendix A - FLACS Dispersion Predictions Versus Measurements

Figure A.1 through Figure A.8 demonstrate the agreement between FLACS predictions and measurements for the wide range of leak conditions specified during testing. In each figure, solid lines of the same color represent the experimental data (solid lines) and predictions (dashed lines) at a specific sensor. The data are separated into four figures corresponding to the height of the sensors.

Example prediction agreement for releases below the display case

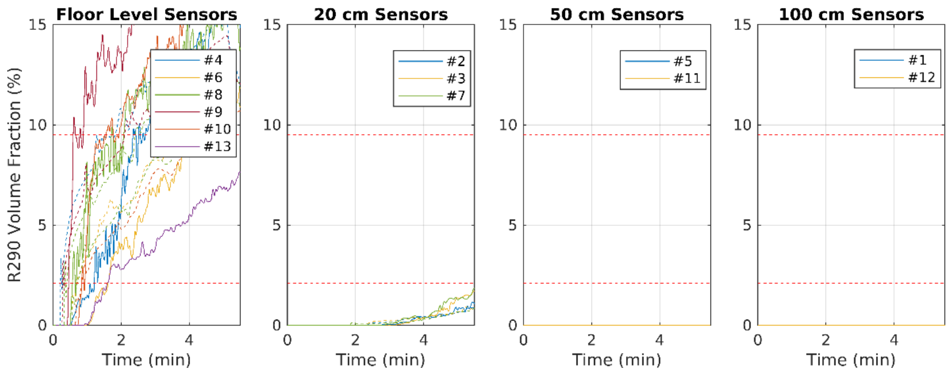

Figure A.1: Typical agreement for bottom releases - 600 g, 120 g/min, condenser fan off.

Example prediction agreement for releases above the display case

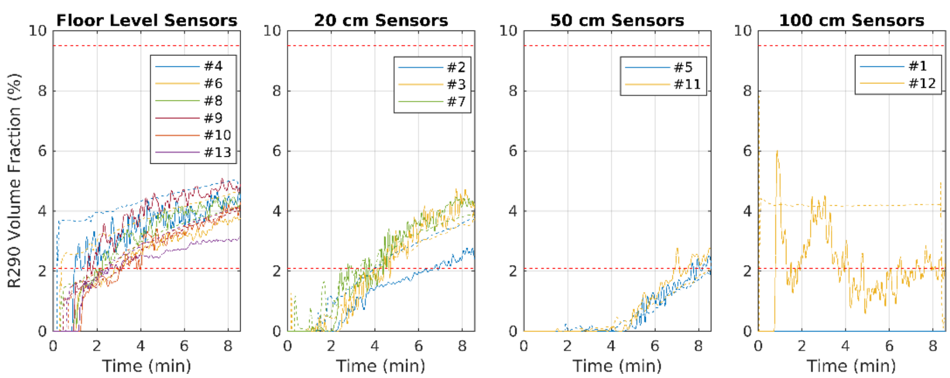

Figure A.2: Top release, 1000 g, 120 g/min, condenser fan off.

Example prediction agreement for releases with low mass flow rate

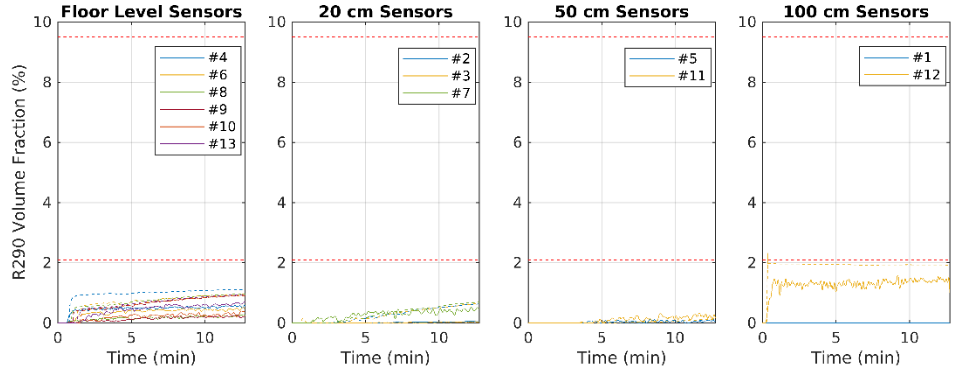

Figure A.3: Top release, 150 g, 12 g/min, condenser fan off.

Example prediction agreement for releases with high mass flow rate

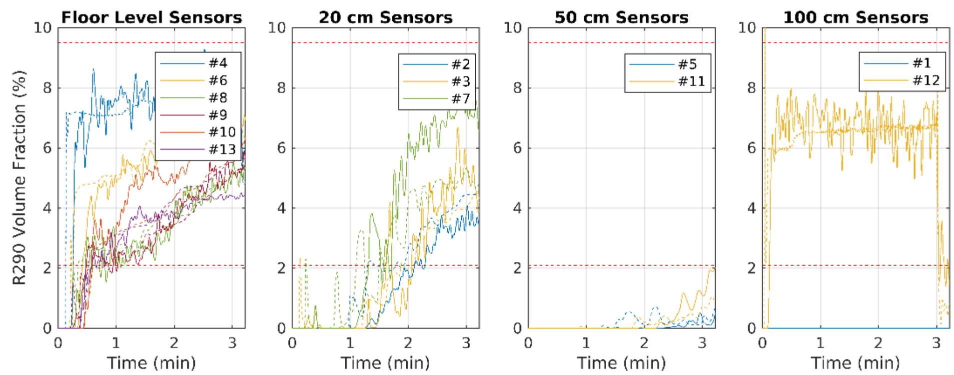

Figure A.4: Top release, 1000 g, 335 g/min, condenser fan off.

Example prediction agreement when releasing small amounts of R-290

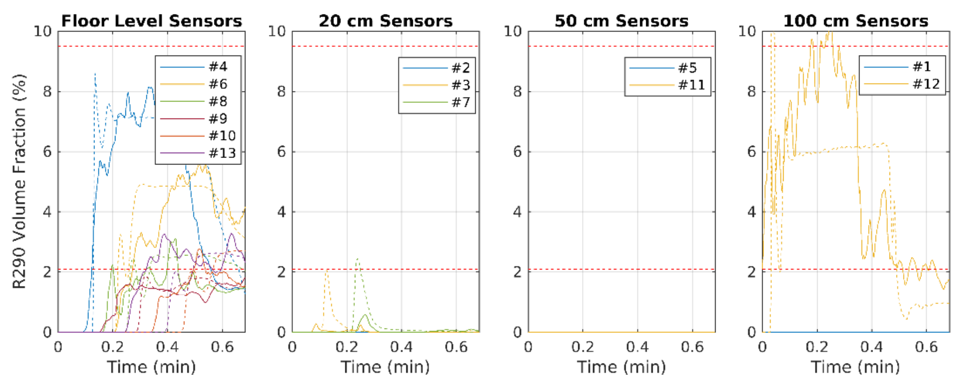

Figure A.5: Top release, 150 g, 335 g/min, condenser fan off.

Example prediction agreement when releasing large amounts of R-290

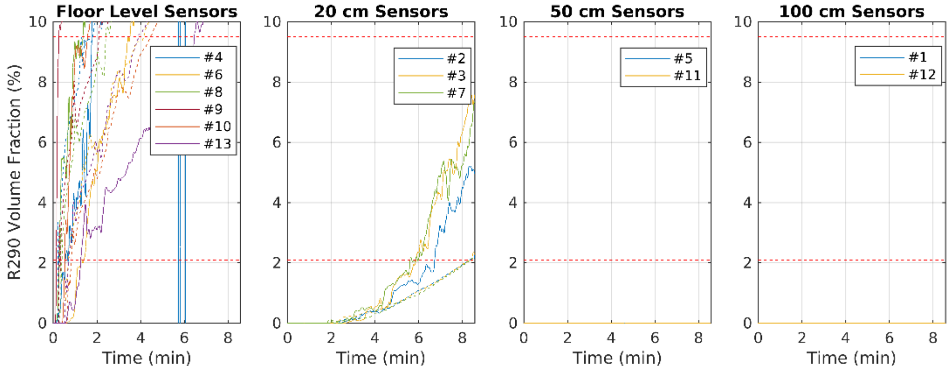

Figure A.6: Bottom release, 1000 g, 120 g/min, condenser fan off.

Example prediction agreement when condenser fan flow rate is low and the R-290 release mass flow rate is high

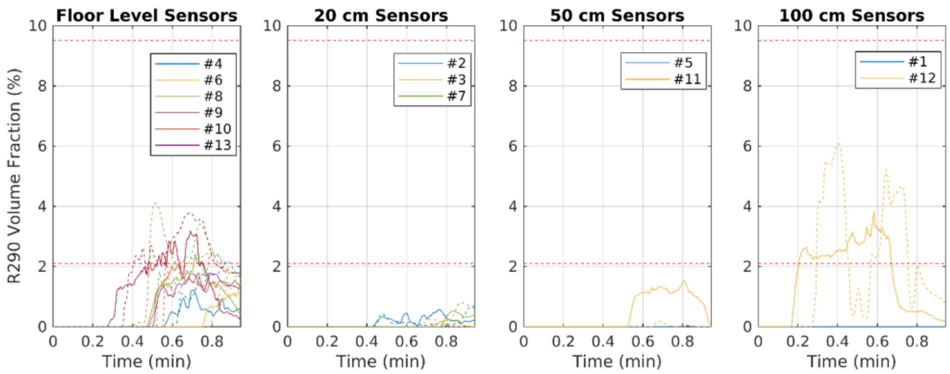

Figure A.7: Bottom release, 150 g, 335 g/min, condenser fan on at 150 m^3/hr.

Example prediction agreement when condenser fan flow rate is high and the R-290 release mass flow rate is low

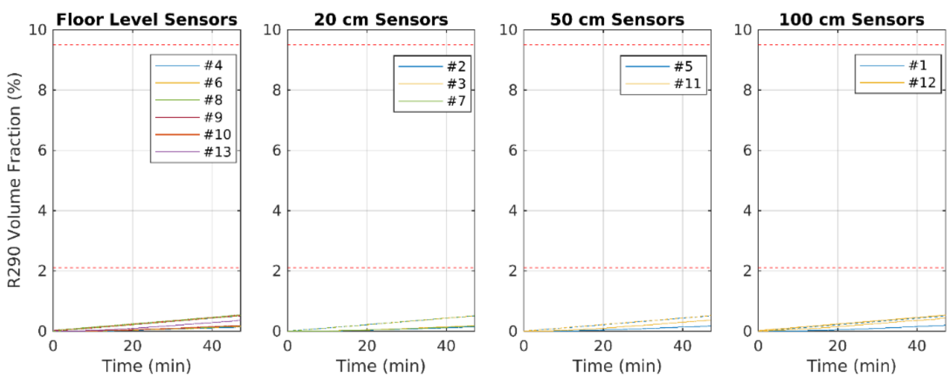

Figure A.8: Bottom release, 1000 g, 12 g/min, condenser fan on at 1000 m^3/hr.

Figure A.9 and Figure A.10 show the largest observed discrepancies between the predictions and measurements to further demonstrate the suitability of FLACS for predicting R-290 releases from a display case. As seen in the figures, predictions are roughly a factor of two or three higher at a few sensors at the floor, however much closer agreement is still observed for the majority of the sensors, and for all sensors located above the floor.

Largest observed discrepancy when the condenser fan was off

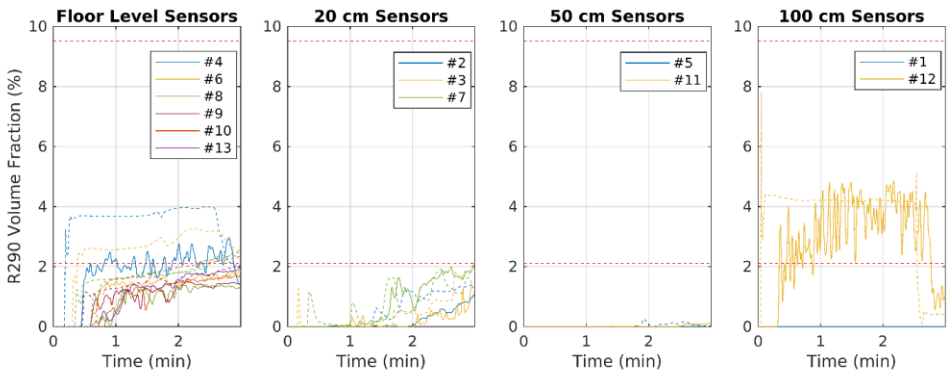

Figure A.9: Top release, 300 g, 120 g/min, condenser fan off.

Largest observed discrepancy when the condenser fan was on

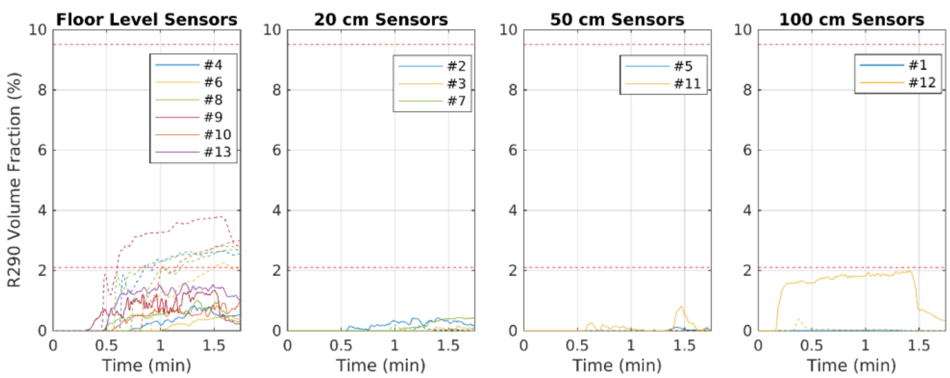

Figure A.10: Bottom release, 150 g, 120 g/min, condenser fans on.

Appendix B - Failure Mode Effects Analysis

Gexcon performed a Failure Modes and Effect Analysis (FMEA) to assess the mechanisms by which refrigerant charges may be accidentally released to the surrounding environment. The FMEA assists in identifying the critical causes and areas associated with releases.

The FMEA is organized by component areas or systems. Instead of looking at each individual component of a refrigeration system, the components expected in a commercial refrigeration unit were grouped into systems or areas as shown in Figure B.1 and listed in Table B.1. For example, the compressor compartment area consists of over a dozen individual components. As such, a failure of any subcomponent is captured as part of the compressor compartment rather than as an individual line item in the FMEA. However, there is significant detail as the impact of many failure modes were applied to each of these areas and their corresponding components.

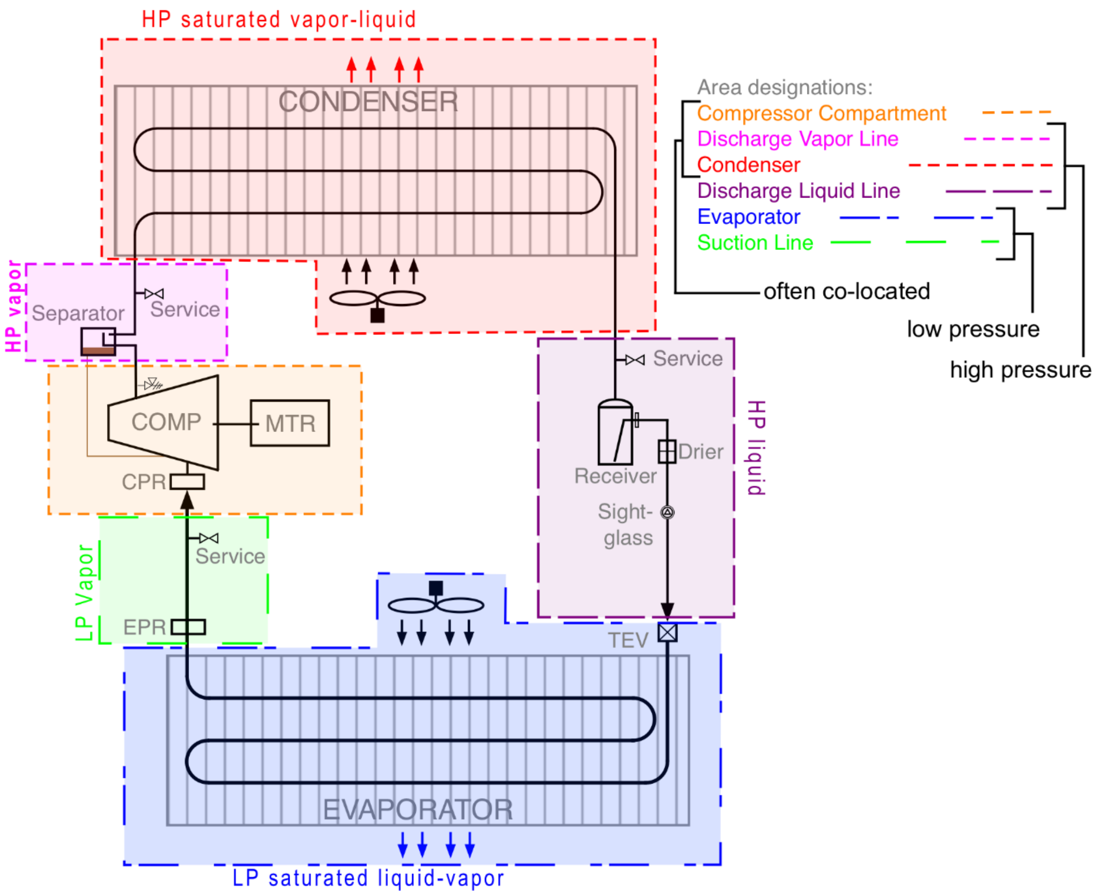

Figure B.1: Area classification diagram showing the six groupings used in the FMEA. Selected components of a typical refrigeration system are shown within the general schematic.

Table B.1: Area classification and components within each area.

System / Area	Consists of the following components *(systems vary and some components listed may not exist in certain applications)*:
Compressor Compartment	compressor motor
	compressor
	shaft
	shaft seals
	hermetic enclosure
	suction and discharge fittings
	internal piping / castings
	electrical connections / wiring
	structural elements and mounting provisions
	oil reservoir system
	crankcase pressure regulator (CPR) valve
	pressure relief valve
	ventilation fan
Discharge Vapor Line	tube length to condenser
	fill and monitor valve
	mechanical connection to compressor discharge
	mechanical connection to condenser
	brazed or welded connections
	oil separator
Condenser	coiled tube length
	cooling fins
	structure
	fan system
	mechanical joints
	brazed joints
Discharge liquid Line	tube length to evaporator
	fill and monitor valve
	mechanical connection to condenser discharge
	mechanical connection to expansion valve
	brazed or welded connections
	sight glass
	receiver
	drier
	discharge gas bypass
	discharge gas bypass solenoid valve
	shut-off valve
	moisture indicator
	solenoid valve
Evaporator	expansion valve
	mechanical connections
	brazed connections
	structure
	fan system
	coiled tube length
	cooling fins
	equalizer line

System / Area	Consists of the following components ***(systems vary and some components listed may not exist in certain applications)*****:**
Suction Line	tube length to compressor
	fill and monitor valve
	mechanical connection to compressor suction
	mechanical connection to evaporator discharge
	brazed or welded connections
	suction accumulator
	EPR valve

With the component areas defined, each one is considered with regard to the failure modes as defined in Table B.2. The approach is such that every component within the area (e.g., compressor shaft seals within the compressor compartment area) is considered against every possible failure mode. It should be noted that in many self-contained refrigeration systems, the first three areas are co-located (Compressor Compartment, Discharge Vapor Line and the Condenser); however, in the interest of a comprehensive and more generally applicable FMEA, these were considered individually.

Table B.2: Established failure modes considered.

Failure Modes	Description
Leaking Pipe (hole)	Line pipe runs, holes and other leaks occurring at the pipe walls, includes brazed joints
Seal / Gland / Core Failure	Leaking valves and shaft seals, other gaskets
Fracture / Rupture / Crack	Pressure relief valve blowing open, cracked receivers, fractured valve bodies
Mechanical Component Failure	Complete major component failure, such as a compressor bearing
Ancillary Component Failure	Sub-systems such as fans or pumps
Leaking Flange / Union / Joint	Mechanical joints, flare connections, compression connections, quick connections
Wall / Case / Housing Thinning	Wall thinning includes abrasion, wear, and general material loss
Monitor / Control hardware	Pressure switches, transducers, gages, etc.

If a failure mode exists for a given area, a cause is specifically identified. The possible causes are applicable to the failure mode under consideration. It is frequent for a cause to be identified across several failure modes (e.g., corrosion). For a more specific example, wall thinning can be caused from an internal source (e.g., contaminant in the refrigerant) or external one (e.g., rubbing).

With the failure modes and potential causes captured, the associated effects were determined. As discussed, the effects appropriate for this research program were limited to refrigerant releases and ignitions sources. If a failure could lead to either of these effects, it was entered into the FMEA. If a failure mode could potentially result in effects beyond loss of refrigerant charge and/or potential source of ignition, those additional effects were not entered.

This process was repeated for every operational mode of a refrigeration system, which are presented in Table B.3.

Table B.3: Operational modes of the refrigeration system.

System Status	Description
Operating	Normal operating use of the unit
Operating - Idle	Compressor off
Off	Charged, functional but turned off
Servicing	Down for in-field maintenance procedures
Installation / Commissioning	Initial installation, setup, charging and test

The FMEA also includes a preliminary qualitative evaluation of relative severity and likelihood. The qualitative evaluation of severity and likelihood are based on information derived from the literature review and provide a foundation for prioritizing failure modes for quantitative evaluation in Section 5 of this report.

For example, a leak in a mechanical joint in the evaporator area caused by external damage was first considered for credibility in all five operational modes. If the failure mode is credible, it was then assessed for severity and likelihood with specific consideration to the system's mode of operation. Typically, failure modes and their associated effects were less likely when the system is *off* and generally more likely and severe during *installation / commissioning*.

In summary, the FMEA captures every operational mode of the display-case type refrigeration system and evaluates for each system: how can it fail, what causes those failures, what are the potential effects (restricted to release and ignition), and how severe and likely is that event. The result of this analysis is a listing of 241 unique entries. Of those, 42 were deemed as not credible, usually a result of the operational status (e.g., the compressor motor can't fail in such a way as to cause a leak if it is off). The complete FMEA is provided in Table B.4.

Table B.4: List of potential failures.

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
1.01	Compressor Compartment	Seal / Gland / Core Failure	seal blow-by due to a) excessive pressure cycling b) excessive wear c) motor runaway causing over-pressurization Seal wear / degradation due to d) age, cycles, use e) loss of resiliency in flexible seals	a) moderate release of R290 charge into the compressor compartment	Operating	III	I
1.02	Compressor Compartment	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow to rapid release of R290 charge into the compressor compartment	Operating	III	II
1.03	Compressor Compartment	Fracture / Rupture / Crack	compressor enclosure crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation e) breached hermetic seal	a) slow to rapid release of R290 charge into the compressor compartment	Operating	III	I
1.04	Compressor Compartment	Mechanical Component Failure	Compressor failure sufficient to breach hermetic seal (not including shaft seal failures which are considered elsewhere) a) electric motor failure b) bearing failure c) shaft failure d) support structure failure e) compressor impeller / rotator failure	a) moderate to rapid release of R290 charge into the compressor compartment b) potential source of ignition	Operating	II	I
1.05	Compressor Compartment	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) PSV failure b) compressor compartment ventilation fan failure c) oil reservoir and separator failure	a) slow to rapid release of R290 charge into the compressor compartment b) potential source of ignition c) reduced ventilation in compressor compartment (if fan failure) d) release of oil into compressor compartment	Operating	III	III

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
1.06	Compressor Compartment	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow to moderate release of R290 charge into the compressor compartment	Operating	II	IV
1.07	Compressor Compartment	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the compressor compartment	Operating	II	III
1.08	Compressor Compartment	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to rapid release of R290 charge into the compressor compartment	Operating	III	II
1.09	Compressor Compartment	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the compressor compartment	Operating - idle	II	I
1.10	Compressor Compartment	Seal / Gland / Core Failure	seal blow-by due to a) excessive pressure cycling b) excessive wear c) motor runaway causing over-pressurization Seal wear / degradation due to d) age, cycles, use e) loss of resiliency in flexible seals	a) slow release of R290 charge into the compressor compartment	Operating - idle	II	II

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
1.11	Compressor Compartment	Fracture / Rupture / Crack	compressor enclosure crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation e) breached hermetic seal	a) slow to moderate release of R290 charge into the compressor compartment	Operating - idle	**II**	**I**
1.12	Compressor Compartment	Mechanical Component Failure	Compressor failure sufficient to breach hermetic seal (not including shaft seal failures which are considered elsewhere) a) electric motor failure b) bearing failure c) shaft failure d) support structure failure e) compressor impeller / rotator failure	a) moderate to rapid release of R290 charge into the compressor compartment b) potential source of ignition	Operating - idle	**I**	**I**
1.13	Compressor Compartment	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) PSV failure b) compressor compartment ventilation fan failure c) oil reservoir and separator failure	a) slow to rapid release of R290 charge into the compressor compartment b) potential source of ignition c) reduced ventilation in compressor compartment (if fan failure) d) release of oil into compressor compartment	Operating - idle	**III**	**III**
1.14	Compressor Compartment	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow to moderate release of R290 charge into the compressor compartment	Operating - idle	**II**	**III**
1.15	Compressor Compartment	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow release of R290 charge into the compressor compartment	Operating - idle	**II**	**I**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
1.16	Compressor Compartment	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions e) corrosion f) seal failure g) external damage h) high voltage	a) slow to moderate release of R290 charge into the compressor compartment	Operating - idle	II	I
1.17	Compressor Compartment	Seal / Gland / Core Failure	Not credible	Not credible	Servicing	I	I
1.18	Compressor Compartment	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the compressor compartment	Servicing	II	I
1.19	Compressor Compartment	Fracture / Rupture / Crack	compressor enclosure crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation e) breached hermetic seal	a) slow to moderate release of R290 charge into the compressor compartment	Servicing	II	I
1.20	Compressor Compartment	Mechanical Component Failure	Not credible	Not credible	Servicing	I	I
1.21	Compressor Compartment	Ancillary Component Failure	Not credible	Not credible	Servicing	I	I
1.22	Compressor Compartment	Leaking Flange / Union / Joint	mechanical connection (including service connections) failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable) e) poor mechanical connection at charge and monitor points	a) slow to moderate release of R290 charge into the compressor compartment	Servicing	III	V

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
1.23	Compressor Compartment	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the compressor compartment	Servicing	**II**	**III**
1.24	Compressor Compartment	Monitor / Control hardware	gauge / switch failure (including servicing equipment) due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to moderate release of R290 charge into the compressor compartment	Servicing	**II**	**III**
1.25	Compressor Compartment	Seal / Gland / Core Failure	seal blow-by due to a) excessive pressure cycling b) excessive wear c) motor runaway causing over-pressurization Seal wear / degradation due to d) age, cycles, use e) loss of resiliency in flexible seals	a) moderate release of R290 charge into the compressor compartment	Installation / Commissioning	**IV**	**I**
1.26	Compressor Compartment	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion (storage / warehouse related) brazed joint failure due to d) weak brazing (un-melted filler) e) filler metal voids / porosity f) base metal erosion in brazed joint g) etched surface in brazing processh) other improper brazing in manufacturing (e.g. wetting and flow)	a) slow to rapid release of R290 charge into the compressor compartment	Installation / Commissioning	**III**	**II**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
1.27	Compressor Compartment	Fracture / Rupture / Crack	compressor enclosure crack due to a) initial pressure cycle b) initial operating environment c) external damage initial pressurized refrigerant charge leading to d) PSV actuation e) breached hermetic seal from assembly	a) slow to rapid release of R290 charge into the compressor compartment	Installation / Commissioning	III	II
1.28	Compressor Compartment	Mechanical Component Failure	Compressor failure upon startup sufficient to breach hermetic seal (not including shaft seal failures which are considered elsewhere) a) electric motor failure b) bearing failure c) shaft failure d) support structure failure e) compressor impeller / rotator failure f) over or under-charging of refrigerant	a) moderate to rapid release of R290 charge into the compressor compartment b) potential source of ignition	Installation / Commissioning	II	II
1.29	Compressor Compartment	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) PSV failure b) compressor compartment ventilation fan failure c) oil reservoir and separator failure	a) slow to rapid release of R290 charge into the compressor compartment b) potential source of ignition c) reduced ventilation in compressor compartment (if fan failure)	Installation / Commissioning	III	III
1.30	Compressor Compartment	Leaking Flange / Union / Joint	mechanical connection (including service connections) failure due to a) excessive stress b) external damage c) corrosion (storage / warehouse related) d) seal deterioration (ferrule, flare or face seal as applicable) e) poor mechanical connection at charge and monitor points	a) slow to moderate release of R290 charge into the compressor compartment	Installation / Commissioning	III	V
1.31	Compressor Compartment	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the compressor compartment	Installation / Commissioning	II	III

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
1.32	Compressor Compartment	Monitor / Control hardware	gauge / switch failure (including servicing equipment) due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion (storage / warehouse related) e) seal failure f) external damage g) high voltage	a) slow to rapid release of R290 charge into the compressor compartment	Installation / Commissioning	**III**	**III**
1.33	Compressor Compartment	Seal / Gland / Core Failure	seal blow-by due to a) excessive pressure cycling b) excessive wear c) motor runaway causing over-pressurization Seal wear / degradation due to d) age, cycles, use e) loss of resiliency in flexible seals	a) slow release of R290 charge into the compressor compartment	Off	**I**	**I**
1.34	Compressor Compartment	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the compressor compartment	Off	**II**	**I**
1.35	Compressor Compartment	Fracture / Rupture / Crack	compressor enclosure crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation e) breached hermetic seal	a) slow to moderate release of R290 charge into the compressor compartment	Off	**II**	**I**
1.36	Compressor Compartment	Mechanical Component Failure	Not credible	Not credible	Off	**I**	**I**
1.37	Compressor Compartment	Ancillary Component Failure	Not credible	Not credible	Off	**I**	**I**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
1.38	Compressor Compartment	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow release of R290 charge into the compressor compartment	Off	II	III
1.39	Compressor Compartment	Abrasion / Wear / Wall Thinning	Not credible	Not credible	Off	II	III
1.40	Compressor Compartment	Monitor / Control hardware	gauge / switch failure due to a) corrosion b) seal failure c) external damage	a) slow to moderate release of R290 charge into the compressor compartment	Off	II	III
2.01	Discharge Vapor Line	Seal / Gland / Core Failure	seal blow-by due to a) excessive pressure cycling b) excessive wear c) motor runaway causing over-pressurization Seal wear / degradation due to d) age, cycles, use e) loss of resiliency in flexible seals	a) moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	III	I
2.02	Discharge Vapor Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	III	II
2.03	Discharge Vapor Line	Fracture / Rupture / Crack	separator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	III	I
2.04	Discharge Vapor Line	Mechanical Component Failure	Not credible	Not credible	Operating	I	I
2.05	Discharge Vapor Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion c) external damage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable) b) potential source of ignition c) rapid release of hot oil into condenser or compressor areas	Operating	III	III

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
2.06	Discharge Vapor Line	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	**II**	**IV**
2.07	Discharge Vapor Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation (entrained oil or impurities) e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	**II**	**III**
2.08	Discharge Vapor Line	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	**II**	**II**
2.09	Discharge Vapor Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	**II**	**I**
2.10	Discharge Vapor Line	Seal / Gland / Core Failure	seal blow-by due to a) excessive pressure cycling b) excessive wear c) motor runaway causing over-pressurization Seal wear / degradation due to d) age, cycles, use e) loss of resiliency in flexible seals	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	**II**	**II**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
2.11	Discharge Vapor Line	Fracture / Rupture / Crack	separator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	**II**	**I**
2.12	Discharge Vapor Line	Mechanical Component Failure	Not credible	Not credible	Operating - idle	**I**	**I**
2.13	Discharge Vapor Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion c) external damage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable) b) potential source of ignition c) moderate release of hot oil into condenser or compressor areas	Operating - idle	**II**	**III**
2.14	Discharge Vapor Line	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	**II**	**III**
2.15	Discharge Vapor Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation (entrained oil or impurities) e) high speed flow f) excessively cold flow causing embrittlement	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	**II**	**I**
2.16	Discharge Vapor Line	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	**II**	**I**
2.17	Discharge Vapor Line	Seal / Gland / Core Failure	Not credible	Not credible	Servicing	**I**	**I**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
2.18	Discharge Vapor Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	II	I
2.19	Discharge Vapor Line	Fracture / Rupture / Crack	separator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	II	I
2.20	Discharge Vapor Line	Mechanical Component Failure	Not credible	Not credible	Servicing	I	I
2.21	Discharge Vapor Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion c) external damage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable) b) potential source of ignition	Servicing	III	II
2.22	Discharge Vapor Line	Leaking Flange / Union / Joint	mechanical connection (including service connections) failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable) e) poor mechanical connection at charge and monitor points	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	III	V
2.23	Discharge Vapor Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation (entrained oil or impurities) e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	II	III

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
2.24	Discharge Vapor Line	Monitor / Control hardware	gauge / switch failure (including servicing equipment) due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions e) corrosion f) seal failure g) external damage h) high voltage	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	II	III
2.25	Discharge Vapor Line	Seal / Gland / Core Failure	seal blow-by due to a) excessive pressure cycling b) excessive wear c) motor runaway causing over-pressurization Seal wear / degradation due to d) age, cycles, use e) loss of resiliency in flexible seals	a) moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	IV	I
2.26	Discharge Vapor Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion (storage / warehouse related) brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	III	II
2.27	Discharge Vapor Line	Fracture / Rupture / Crack	separator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damageover-pressurization leading to d) PSV actuation	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	III	II
2.28	Discharge Vapor Line	Mechanical Component Failure	Not credible	Not credible	Installation / Commissioning	I	I
2.29	Discharge Vapor Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion (storage / warehouse related) c) external damage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable) b) potential source of ignition c) rapid release of hot oil into condenser or compressor areas	Installation / Commissioning	III	III

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
2.30	Discharge Vapor Line	Leaking Flange / Union / Joint	mechanical connection (including service connections) failure due to a) excessive stress b) external damage c) corrosion (storage / warehouse related) d) seal deterioration (ferrule, flare or face seal as applicable) e) poor mechanical connection at charge and monitor points	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	**III**	**V**
2.31	Discharge Vapor Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation (entrained oil or impurities) e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	**II**	**III**
2.32	Discharge Vapor Line	Monitor / Control hardware	gauge / switch failure (including servicing equipment) due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions e) corrosion (storage / warehouse related) f) seal failure g) external damage h) high voltage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	**III**	**III**
2.33	Discharge Vapor Line	Seal / Gland / Core Failure	seal blow-by due to a) excessive pressure cycling b) excessive wear c) motor runaway causing over-pressurizationSeal wear / degradation due to d) age, cycles, use e) loss of resiliency in flexible seals	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	**II**	**I**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
2.34	Discharge Vapor Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	II	II
2.35	Discharge Vapor Line	Fracture / Rupture / Crack	separator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	II	I
2.36	Discharge Vapor Line	Mechanical Component Failure	Not credible	Not credible	Off	I	I
2.37	Discharge Vapor Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion c) external damage	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	II	III
2.38	Discharge Vapor Line	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	II	I
2.39	Discharge Vapor Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation (entrained oil or impurities) e) high speed flow f) excessively cold flow causing embrittlement	Not credible	Off	II	I

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
2.40	Discharge Vapor Line	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failureg) external damage f) high voltage	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	II	I
3.01	Condenser	Seal / Gland / Core Failure	seal blow-by due to a) excessive pressure cycling b) excessive wear c) motor runaway causing over-pressurization Seal wear / degradation due to d) age, cycles, use e) loss of resiliency in flexible seals	a) moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Operating	III	I
3.02	Condenser	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow to rapid release of R290 charge into the condenser area (which may be the compressor compartment)	Operating	III	II
3.03	Condenser	Fracture / Rupture / Crack	separator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to rapid release of R290 charge into the condenser area (which may be the compressor compartment)	Operating	III	I
3.04	Condenser	Mechanical Component Failure	Not credible	Not credible	Operating	I	I
3.05	Condenser	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) PSV failure b) condenser fan failure c) condenser support structure failure d) external damage	a) slow to rapid release of R290 charge into the condenser area (which may be the compressor compartment) b) potential source of ignition c) reduced ventilation in compressor compartment (if condenser fan serves as compressor compartment fan)	Operating	III	III

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
3.06	Condenser	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow to moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Operating	II	IV
3.07	Condenser	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Operating	II	III
3.08	Condenser	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions e) corrosion f) seal failure g) external damage h) high voltage	a) slow to rapid release of R290 charge into the condenser area (which may be the compressor compartment)	Operating	II	II
3.09	Condenser	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the condenser area (which may be the compressor compartment)	Operating - idle	II	I
3.10	Condenser	Seal / Gland / Core Failure	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the condenser area (which may be the compressor compartment)	Operating - idle	II	II

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
3.11	Condenser	Fracture / Rupture / Crack	separator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Operating - idle	II	I
3.12	Condenser	Mechanical Component Failure	Not credible	Not credible	Operating - idle	I	I
3.13	Condenser	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) PSV failure b) condenser fan failure c) condenser support structure failure d) external damage	a) slow to rapid release of R290 charge into the condenser area (which may be the compressor compartment) b) potential source of ignitionc) reduced ventilation in compressor compartment (if condenser fan serves as compressor compartment fan)	Operating - idle	II	III
3.14	Condenser	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow to moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Operating - idle	II	III
3.15	Condenser	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion	a) slow release of R290 charge into the condenser area (which may be the compressor compartment)	Operating - idle	I	I
3.16	Condenser	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Operating - idle	II	I
3.17	Condenser	Seal / Gland / Core Failure	Not credible	Not credible	Servicing	I	I

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
3.18	Condenser	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the condenser area (which may be the compressor compartment)	Servicing	**II**	**I**
3.19	Condenser	Fracture / Rupture / Crack	separator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Servicing	**II**	**I**
3.20	Condenser	Mechanical Component Failure	Not credible	Not credible	Servicing	**I**	**I**
3.21	Condenser	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) PSV failure b) condenser fan failure c) condenser support structure failure d) external damage	a) slow to rapid release of R290 charge into the condenser area (which may be the compressor compartment) b) potential source of ignitionc) reduced ventilation in compressor compartment (if condenser fan serves as compressor compartment fan)	Servicing	**III**	**II**
3.22	Condenser	Leaking Flange / Union / Joint	mechanical connection (including service connections) failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable) e) poor mechanical connection at charge and monitor points	a) slow to moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Servicing	**III**	**V**
3.23	Condenser	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion	a) slow release of R290 charge into the condenser area (which may be the compressor compartment)	Servicing	**I**	**II**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
3.24	Condenser	Monitor / Control hardware	gauge / switch failure (including servicing equipment) due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Servicing	**II**	**III**
3.25	Condenser	Seal / Gland / Core Failure	seal blow-by due to a) excessive pressure cycling b) excessive wear c) motor runaway causing over-pressurization Seal wear / degradation due to d) age, cycles, use e) loss of resiliency in flexible seals	a) moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Installation / Commissioning	**IV**	**I**
3.26	Condenser	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion (storage / warehouse related) brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow to rapid release of R290 charge into the condenser area (which may be the compressor compartment)	Installation / Commissioning	**III**	**II**
3.27	Condenser	Fracture / Rupture / Crack	separator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to rapid release of R290 charge into the condenser area (which may be the compressor compartment)	Installation / Commissioning	**III**	**II**
3.28	Condenser	Mechanical Component Failure	Not credible	Not credible	Installation / Commissioning	**I**	**I**
3.29	Condenser	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) PSV failure b) condenser fan failure c) condenser support structure failure d) external damage	a) slow to rapid release of R290 charge into the condenser area (which may be the compressor compartment) b) potential source of ignition c) reduced ventilation in compressor compartment (if condenser fan serves as compressor compartment fan)	Installation / Commissioning	**III**	**III**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
3.30	Condenser	Leaking Flange / Union / Joint	mechanical connection (including service connections) failure due to a) excessive stress b) external damage c) corrosion (storage / warehouse related) d) seal deterioration (ferrule, flare or face seal as applicable) e) poor mechanical connection at charge and monitor points	a) slow to moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Installation / Commissioning	**III**	**V**
3.31	Condenser	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Installation / Commissioning	**II**	**III**
3.32	Condenser	Monitor / Control hardware	gauge / switch failure (including servicing equipment) due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion (storage / warehouse related) e) seal failure f) external damage g) high voltage	a) slow to rapid release of R290 charge into the condenser area (which may be the compressor compartment)	Installation / Commissioning	**III**	**III**
3.33	Condenser	Seal / Gland / Core Failure	seal blow-by due to a) excessive pressure cycling b) excessive wear c) motor runaway causing over-pressurization seal wear / degradation due to d) age, cycles, use e) loss of resiliency in flexible seals	a) slow release of R290 charge into the condenser area (which may be the compressor compartment)	Off	**II**	**I**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
3.34	Condenser	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the condenser area (which may be the compressor compartment)	Off	II	I
3.35	Condenser	Fracture / Rupture / Crack	separator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Off	II	I
3.36	Condenser	Mechanical Component Failure	Not credible	Not credible	Off	I	I
3.37	Condenser	Ancillary Component Failure	Not credible	a) slow to rapid release of R290 charge into the condenser area (which may be the compressor compartment) b) potential source of ignition c) reduced ventilation in compressor compartment (if condenser fan serves as compressor compartment fan)	Off	II	III
3.38	Condenser	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow release of R290 charge into the condenser area (which may be the compressor compartment)	Off	II	I
3.39	Condenser	Abrasion / Wear / Wall Thinning	Not credible	Not credible	Off	II	I
3.40	Condenser	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to moderate release of R290 charge into the condenser area (which may be the compressor compartment)	Off	II	I

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
4.01	Discharge Liquid Line	Seal / Gland / Core Failure	liquid receiver gasket / seal degradation due to a) age, cycles, use b) corrosionc) embrittlement	a) rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	IV	I
4.02	Discharge Liquid Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	IV	II
4.03	Discharge Liquid Line	Fracture / Rupture / Crack	liquid receiver or drier housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation sight-glass / shut-off valve / moisture indicator failure due to e) corrosion f) external damage g) age, cycles, fatigue	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	IV	I
4.04	Discharge Liquid Line	Mechanical Component Failure	Not credible	Not credible	Operating	I	I
4.05	Discharge Liquid Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion c) external damage	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable) b) potential source of ignition	Operating	IV	III
4.06	Discharge Liquid Line	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	III	IV

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
4.07	Discharge Liquid Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	III	III
4.08	Discharge Liquid Line	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	III	II
4.09	Discharge Liquid Line	Leaking Pipe (hole)	liquid receiver gasket / seal degradation due to a) age, cycles, use b) corrosion c) embrittlement	a) moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	III	I
4.10	Discharge Liquid Line	Seal / Gland / Core Failure	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	III	II
4.11	Discharge Liquid Line	Fracture / Rupture / Crack	liquid receiver or drier housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation sight-glass / shut-off valve / moisture indicator failure due to e) corrosion f) external damage g) age, cycles, fatigue	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	III	I

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
4.12	Discharge Liquid Line	Mechanical Component Failure	Not credible	Not credible	Operating - idle	I	I
4.13	Discharge Liquid Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion c) external damage	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable) b) potential source of ignition	Operating - idle	III	III
4.14	Discharge Liquid Line	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	III	III
4.15	Discharge Liquid Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere).External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	II	I
4.16	Discharge Liquid Line	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	III	I
4.17	Discharge Liquid Line	Seal / Gland / Core Failure	Not credible	Not credible	Servicing	I	I

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
4.18	Discharge Liquid Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	**III**	**I**
4.19	Discharge Liquid Line	Fracture / Rupture / Crack	liquid receiver or drier housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation sight-glass / shut-off valve / moisture indicator failure due to e) corrosion f) external damage g) age, cycles, fatigue	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	**III**	**I**
4.20	Discharge Liquid Line	Mechanical Component Failure	Not credible	Not credible	Servicing	**I**	**I**
4.21	Discharge Liquid Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion c) external damage	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable) b) potential source of ignition	Servicing	**IV**	**II**
4.22	Discharge Liquid Line	Leaking Flange / Union / Joint	mechanical connection (including service connections) failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable) e) poor mechanical connection at charge and monitor points	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	**IV**	**V**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
4.23	Discharge Liquid Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	**II**	**II**
4.24	Discharge Liquid Line	Monitor / Control hardware	gauge / switch failure (including servicing equipment) due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	**II**	**III**
4.25	Discharge Liquid Line	Seal / Gland / Core Failure	liquid receiver gasket / seal degradation due to a) age, cycles, use b) corrosion (storage / warehouse related) c) embrittlement	a) rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	**V**	**I**
4.26	Discharge Liquid Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion (storage / warehouse related) brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	**IV**	**II**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
4.27	Discharge Liquid Line	Fracture / Rupture / Crack	liquid receiver or drier housing crack due to a) excessive thermal cyclesb) excessive vibrationsc) external damageover-pressurization leading tod) PSV actuationsight-glass / shut-off valve / moisture indicator failure due toe) corrosion (storage / warehouse related)f) external damageh) age, cycles, fatigue	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	IV	II
4.28	Discharge Liquid Line	Mechanical Component Failure	Not credible	Not credible	Installation / Commissioning	I	I
4.29	Discharge Liquid Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion (storage / warehouse related) c) external damage	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable) b) potential source of ignition	Installation / Commissioning	IV	III
4.30	Discharge Liquid Line	Leaking Flange / Union / Joint	mechanical connection (including service connections) failure due to a) excessive stress b) external damage c) corrosion (storage / warehouse related) d) seal deterioration (ferrule, flare or face seal as applicable) e) poor mechanical connection at charge and monitor points	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	IV	V
4.31	Discharge Liquid Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	III	III

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
4.32	Discharge Liquid Line	Monitor / Control hardware	gauge / switch failure (including servicing equipment) due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion (storage / warehouse related) e) seal failure f) external damage g) high voltage	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	IV	III
4.33	Discharge Liquid Line	Seal / Gland / Core Failure	liquid receiver gasket / seal degradation due to a) age, cycles, use b) corrosion c) embrittlement	a) moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	III	I
4.34	Discharge Liquid Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	III	II
4.35	Discharge Liquid Line	Fracture / Rupture / Crack	liquid receiver or drier housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation sight-glass / shut-off valve / moisture indicator failure due to e) corrosion f) external damage g) age, cycles, fatigue	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	III	I
4.36	Discharge Liquid Line	Mechanical Component Failure	Not credible	Not credible	Off	I	I
4.37	Discharge Liquid Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion c) external damage	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable) b) potential source of ignition	Off	III	III

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
4.38	Discharge Liquid Line	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	III	I
4.39	Discharge Liquid Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	III	I
4.40	Discharge Liquid Line	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) moderate to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	III	I
5.01	Evaporator	Seal / Gland / Core Failure	expansion throttling valve gasket / seal degradation due to a) age, cycles, use b) corrosion c) embrittlement	a) moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Operating	III	I
5.02	Evaporator	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow to rapid release of R290 charge into the refrigerated area via evaporator fan forced convection	Operating	III	II

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
5.03	Evaporator	Fracture / Rupture / Crack	expansion throttling valve housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to rapid release of R290 charge into the refrigerated area via evaporator fan forced convection	Operating	**III**	**I**
5.04	Evaporator	Mechanical Component Failure	Not credible	Not credible	Operating	**I**	**I**
5.05	Evaporator	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) PSV failure b) evaporator fan failure c) evaporator support structure failure d) external damage	a) slow to rapid release of R290 charge into the refrigerated area via evaporator fan forced convection b) potential source of ignition c) excessively cold operation in evaporator	Operating	**III**	**III**
5.06	Evaporator	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Operating	**II**	**IV**
5.07	Evaporator	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Operating	**II**	**III**
5.08	Evaporator	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to rapid release of R290 charge into the refrigerated area via evaporator fan forced convection	Operating	**II**	**II**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
5.09	Evaporator	Leaking Pipe (hole)	expansion throttling valve gasket / seal degradation due to a) age, cycles, use b) corrosion c) embrittlement	a) slow release of R290 charge into the refrigerated area via evaporator fan forced convection	Operating - idle	II	I
5.10	Evaporator	Seal / Gland / Core Failure	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the refrigerated area via evaporator fan forced convection	Operating - idle	II	II
5.11	Evaporator	Fracture / Rupture / Crack	expansion throttling valve housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Operating - idle	II	I
5.12	Evaporator	Mechanical Component Failure	Not credible	Not credible	Operating - idle	I	I
5.13	Evaporator	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) PSV failure b) evaporator fan failure c) evaporator support structure failure d) external damage	a) slow to rapid release of R290 charge into the refrigerated area via evaporator fan forced convection b) potential source of ignition c) moderate release of hot oil from reservoir / separator into condenser or compressor areas.	Operating - idle	II	III
5.14	Evaporator	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Operating - idle	II	III

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
5.15	Evaporator	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow release of R290 charge into the refrigerated area via evaporator fan forced convection	Operating - idle	II	I
5.16	Evaporator	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Operating - idle	II	I
5.17	Evaporator	Seal / Gland / Core Failure	Not credible	Not credible	Servicing	I	I
5.18	Evaporator	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the refrigerated area via evaporator fan forced convection	Servicing	II	I
5.19	Evaporator	Fracture / Rupture / Crack	expansion throttling valve housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Servicing	II	I
5.20	Evaporator	Mechanical Component Failure	Not credible	Not credible	Servicing	I	I

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
5.21	Evaporator	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) PSV failure b) evaporator fan failure c) evaporator support structure failure d) external damage	a) slow to rapid release of R290 charge into the refrigerated area via evaporator fan forced convection b) potential source of ignition c) high fuel concentration in compressor compartment	Servicing	III	II
5.22	Evaporator	Leaking Flange / Union / Joint	mechanical connection (including service connections) failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable) e) poor mechanical connection at charge and monitor points	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Servicing	III	V
5.23	Evaporator	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Servicing	II	III
5.24	Evaporator	Monitor / Control hardware	gauge / switch failure (including servicing equipment) due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Servicing	II	III
5.25	Evaporator	Seal / Gland / Core Failure	expansion throttling valve gasket / seal degradation due to a) age, cycles, use b) corrosion (storage / warehouse related) c) embrittlement	a) moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Installation / Commissioning	IV	I

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
5.26	Evaporator	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion (storage / warehouse related) brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow to rapid release of R290 charge into the refrigerated area via evaporator fan forced convection	Installation / Commissioning	III	II
5.27	Evaporator	Fracture / Rupture / Crack	expansion throttling valve housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to rapid release of R290 charge into the refrigerated area via evaporator fan forced convection	Installation / Commissioning	III	II
5.28	Evaporator	Mechanical Component Failure	Not credible	Not credible	Installation / Commissioning	I	I
5.29	Evaporator	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) PSV failure b) evaporator fan failure c) evaporator support structure failure d) external damage	a) slow to rapid release of R290 charge into the refrigerated area via evaporator fan forced convection b) potential source of ignition c) excessively cold operation in evaporator	Installation / Commissioning	III	III
5.30	Evaporator	Leaking Flange / Union / Joint	mechanical connection (including service connections) failure due to a) excessive stress b) external damage c) corrosion (storage / warehouse related) d) seal deterioration (ferrule, flare or face seal as applicable) e) poor mechanical connection at charge and monitor points	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Installation / Commissioning	III	V

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
5.31	Evaporator	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Installation / Commissioning	II	III
5.32	Evaporator	Monitor / Control hardware	gauge / switch failure (including servicing equipment) due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion (storage / warehouse related) e) seal failure f) external damage g) high voltage	a) slow to rapid release of R290 charge into the refrigerated area via evaporator fan forced convection	Installation / Commissioning	III	III
5.33	Evaporator	Seal / Gland / Core Failure	expansion throttling valve gasket / seal degradation due to a) age, cycles, use b) corrosion c) embrittlement	a) slow release of R290 charge into the refrigerated area via evaporator fan forced convection	Off	II	I
5.34	Evaporator	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the refrigerated area via evaporator fan forced convection	Off	II	II
5.35	Evaporator	Fracture / Rupture / Crack	expansion throttling valve housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage over-pressurization leading to d) PSV actuation	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Off	II	I
5.36	Evaporator	Mechanical Component Failure	Not credible	Not credible	Off	I	I

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
5.37	Evaporator	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) PSV failure b) evaporator fan failure c) evaporator support structure failure d) external damage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area in addition to airflow over condenser b) potential source of ignition	Off	**II**	III
5.38	Evaporator	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow release of R290 charge into the refrigerated area via evaporator fan forced convection	Off	**II**	**I**
5.39	Evaporator	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	Not credible	Off	**II**	**I**
5.40	Evaporator	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to moderate release of R290 charge into the refrigerated area via evaporator fan forced convection	Off	**II**	**I**
6.01	Suction Line	Seal / Gland / Core Failure	suction accumulator gasket / seal degradation due to a) age, cycles, use b) corrosion c) embrittlement	a) moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	III	**I**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
6.02	Suction Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	**III**	**II**
6.03	Suction Line	Fracture / Rupture / Crack	suction accumulator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	**III**	**I**
6.04	Suction Line	Mechanical Component Failure	Not credible	Not credible	Operating	**I**	**I**
6.05	Suction Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion c) external damage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	**III**	**III**
6.06	Suction Line	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	**II**	**IV**
6.07	Suction Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	**II**	**III**

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
6.08	Suction Line	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating	II	II
6.09	Suction Line	Leaking Pipe (hole)	suction accumulator gasket / seal degradation due to a) age, cycles, use b) corrosion c) embrittlement	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	II	I
6.10	Suction Line	Seal / Gland / Core Failure	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	II	II
6.11	Suction Line	Fracture / Rupture / Crack	suction accumulator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	II	I
6.12	Suction Line	Mechanical Component Failure	Not credible	Not credible	Operating - idle	I	I
6.13	Suction Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion c) external damage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	II	III
6.14	Suction Line	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	II	III

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
6.15	Suction Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	II	I
6.16	Suction Line	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Operating - idle	II	I
6.17	Suction Line	Seal / Gland / Core Failure	Not credible	Not credible	Servicing	I	I
6.18	Suction Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	II	I
6.19	Suction Line	Fracture / Rupture / Crack	suction accumulator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	II	I
6.20	Suction Line	Mechanical Component Failure	Not credible	Not credible	Servicing	I	I
6.21	Suction Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion c) external damage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	III	II

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
6.22	Suction Line	Leaking Flange / Union / Joint	mechanical connection (including service connections) failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable) e) poor mechanical connection at charge and monitor points	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	III	V
6.23	Suction Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	II	III
6.24	Suction Line	Monitor / Control hardware	gauge / switch failure (including servicing equipment) due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Servicing	II	III
6.25	Suction Line	Seal / Gland / Core Failure	suction accumulator gasket / seal degradation due to a) age, cycles, use b) corrosion (storage / warehouse related) c) embrittlement	a) moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	IV	I
6.26	Suction Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion (storage / warehouse related) brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	III	II

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
6.27	Suction Line	Fracture / Rupture / Crack	suction accumulator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	III	II
6.28	Suction Line	Mechanical Component Failure	Not credible	Not credible	Installation / Commissioning	I	I
6.29	Suction Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion (storage / warehouse related) c) external damage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	III	III
6.30	Suction Line	Leaking Flange / Union / Joint	mechanical connection (including service connections) failure due to a) excessive stress b) external damage c) corrosion (storage / warehouse related) d) seal deterioration (ferrule, flare or face seal as applicable) e) poor mechanical connection at charge and monitor points	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	III	V
6.31	Suction Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	II	III
6.32	Suction Line	Monitor / Control hardware	gauge / switch failure (including servicing equipment) due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion (storage / warehouse related) e) seal failure f) external damage g) high voltage	a) slow to rapid release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Installation / Commissioning	III	III

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
6.33	Suction Line	Seal / Gland / Core Failure	suction accumulator gasket / seal degradation due to a) age, cycles, use b) corrosion c) embrittlement	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	II	I
6.34	Suction Line	Leaking Pipe (hole)	pipe wall integrity degradation due to a) over-pressurization b) external damage c) corrosion brazed joint failure due to d) stress cracking e) filler metal voids / porosity f) base metal erosion in brazed joint	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	II	II
6.35	Suction Line	Fracture / Rupture / Crack	suction accumulator housing crack due to a) excessive thermal cycles b) excessive vibrations c) external damage	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	II	I
6.36	Suction Line	Mechanical Component Failure	Not credible	Not credible	Off	I	I
6.37	Suction Line	Ancillary Component Failure	complete subsystem failure (excluding cracked or fractured case which is considered elsewhere) a) over-pressurization b) corrosion c) external damage	not credible	Off	II	III
6.38	Suction Line	Leaking Flange / Union / Joint	mechanical connection failure due to a) excessive stress b) external damage c) corrosion d) seal deterioration (ferrule, flare or face seal as applicable)	a) slow release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	II	I

No.	Component Area	Failure Mode	Potential Cause(s)	Effect(s)	State	Severity	Likelihood
6.39	Suction Line	Abrasion / Wear / Wall Thinning	specific pipe/tube failure due to wall thinning (excludes hole failure modes addressed elsewhere). External thinning due to a) contact abrasion (rubbing) b) atmospheric debris (such as sand) pitting and abrasion Internal thinning due to c) flow abrasion / contaminate in refrigerant d) cavitation e) high speed flow f) excessively cold flow causing embrittlement	Not credible	Off	II	I
6.40	Suction Line	Monitor / Control hardware	gauge / switch failure due to a) over-pressurization b) excessive cycles (amplitude or frequency) fatigue c) extreme temperature / pressure conditions d) corrosion e) seal failure f) external damage g) high voltage	a) slow to moderate release of R290 charge into the compressor compartment and/or condenser area (if applicable)	Off	II	I