AHRI Project 8004 Final Report

Risk Assessment of Residential Heat Pump Systems Using 2L Flammable Refrigerants

Prepared for

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Executive Summary

There is currently world-wide interest in developing substitutes for materials whose environmental release may contribute to global climate change. R-410A, the primary refrigerant used in residential AC systems and heat pumps, is a greenhouse gas with a global warming potential of 2,100. Possible replacements for R-410A in residential applications include ASHRAE Class 2L refrigerants, which have reduced global warming potential but are mildly flammable. Although normal operation poses negligible risk, accidental releases due to equipment faults or fatigue could potentially result in refrigerant ignition if a sufficient ignition source is also present. To better characterize these risks, Gradient conducted a risk assessment to evaluate the use of three Class 2L refrigerants (R-32, R-1234yf, and R-1234ze(E)) in residential split heat pump systems. The work included CFD modeling, experimental measurements, and a fault tree analysis (FTA) to quantify ignition risks. The charge amounts used in the assessments were those that would be typical of a 3-ton heat pump. The assessment indicated that large accidental releases of R-32, R-1234yf, and R-1234ze(E) (*i.e.*, on the order of 170 g/s for R-32, 78 g/s for R-1234yf and ze(E)) could create flammable concentrations in a very narrow area immediately in front of the leak location for heat pump units installed in basements, garages, or attics, but that refrigerant concentrations in the majority of each room would be substantially below the lower flammable limit (LFL). Further, the assessment found that large releases of these refrigerants from a heat pump unit located in a utility closet can produce concentrations above the LFL, although the refrigerant exceeds the LFL only briefly (approximately 70 s for R-32 and R-1234yf and 45 s for R-1234ze(E)). Flammable concentrations did not occur with smaller leaks of R-32, R-1234ze(E) or R-1234yf (*e.g.*, 1.5 g/s or less) in utility closets. Incorporating these findings, the FTA estimated that the risks of refrigerant ignition due to an accidental refrigerant leak of R-32, R-1234yf, and R-1234ze(E) were 9×10^{-5}, 2×10^{-5}, and 2×10^{-5} events per unit per year, respectively. For comparison, the overall risk of a significant home fire in the US is 1×10^{-3} per home per year. For all three refrigerants, the risk of ignition was highest in the scenario involving release in the outdoor portion of the unit. When considering indoor leaks only, the ignition risks for R-32, R-1234yf, and R-1234ze(E) were 7×10^{-8}, 8×10^{-9}, and 3×10^{-10} events per unit per year respectively. The FTA in this study considered refrigerant ignition and did not determine whether a fire would ensue due to the ignition of surrounding materials. The analysis also did not include potential mitigation factors that would further reduce the probability of refrigerant ignition. All heat pump systems were assumed to contain the same mass of refrigerant charge.

1 Introduction

In accordance with the Montreal Protocol, which addresses threats of ozone depletion, governments world-wide instituted a phase-out of the use of chlorodifluoromethane (R-22) – including its use in residential climate control applications – beginning in 1996. As a result of this action, most newly manufactured air conditioning systems and heat pumps in the United States use R-410A as the refrigerant (US EPA, 2010a). R-410A is a 50:50 (by weight) blend of R-32 (difluoromethane) and R-125 (pentafluoroethane). Although R-410A has zero ozone depletion potential (ODP), it is a greenhouse gas with a global warming potential (GWP) of 2,100 (based on a 100-year time horizon, IPCC-AR4, 2007). There is therefore world-wide interest in developing new low-GWP refrigerants to address global climate change concerns. One class of potential replacement refrigerants exhibit relatively low GWP but mild flammability (*i.e.*, ASHRAE-34/ISO-817 Class 2L). These refrigerants would provide a significant environmental benefit if they could be successfully adopted for use in stationary air conditioning and refrigeration applications (Powell, 2011). One low-GWP 2L refrigerant, R-1234yf (2,3,3,3-tetrafluoropropene), has recently been identified as suitable for use in automotive air conditioning (Gradient, 2009; US EPA, 2011), but significant differences between automotive and residential climate control systems preclude direct extrapolation between these uses. An earlier evaluation of another 2L refrigerant, R-32, for use in heat pump systems (Goetzler *et al.*, 1998) reported a low risk of fire – approximately four fires per million units per year from leaks during operation and system service.[1] While informative, the Goetzler *et al.* study was conducted more than a decade ago and may not reflect current technologies or procedures used in heat pump design and service. It also does not include several newer refrigerants that may be good candidates for use in heat pump systems. The current risk assessment, carried out as a cooperative industry effort coordinated by the Air-Conditioning, Heating and Refrigeration Institute (AHRI), explores more broadly whether 2L refrigerants may be used safely in heat pumps for residential settings given current technologies.

As used in the context of this evaluation, risk is the likelihood or probability that leaked refrigerant from a residential heat pump system is ignited. Risks are evaluated and quantified through the process of risk assessment. Like all risk assessments, the risk assessment of a potential alternative refrigerant is a multi-step process. An early step in the process is to consider the possible scenarios under which the refrigerant could leak and be ignited. It is then necessary to gather data to support a quantitative estimation of the risk associated with that particular event. Once all of the potential scenarios are identified and the necessary data collected, the data are brought together to develop a mathematical estimate of potential risk.

The current risk assessment consisted of the following steps:

1. An assessment of the flammability of the candidate refrigerants, including determining the upper and lower flammable limits, the minimum ignition energy, the autoignition temperature, and the fundamental burning velocity.
2. Consideration of toxicity data available for each refrigerant, including safe levels of exposure for acute and chronic exposure situations.

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[1] Goetzler *et al*. described the adverse outcome in their analysis as a fire but in reality they evaluated refrigerant ignition. Because 2L refrigerants produce weak flames which may not be sufficient to ignite other materials (consistent with what the general public would consider to be a "fire"), we define the adverse outcome in the current analysis as refrigerant ignition.

3. An assessment of potential refrigerant concentrations in air in the event of an accidental refrigerant release in different locations in a home where a heat pump could be located.
4. Research on the probabilities and frequencies of events contributing to accidental releases of refrigerant under different situations (*e.g.*, system on, system off, during repair) and potential leak rates. Where specific data were not available, consensus values were developed based on the expertise of professionals familiar with heat pump engineering and system failure mechanisms.
5. Data from the previous four steps were then combined to estimate the overall risk of refrigerant ignition through the use of fault tree analysis (FTA). The results were then considered in the context of other commonly encountered life events which may involve adverse effects.

2 Properties of Alternative Refrigerants Under Study

The risk assessment evaluated three refrigerants: R-1234yf (2,3,3,3-tetrafluoropropene), R-1234ze(E) (trans-1,1,1,3-tetrafluoropropene), and R-32 (1,1-difluoromethane). R-1234yf and R-1234ze(E) are new refrigerants developed to address concerns related to the greenhouse gas properties of existing fluoroalkane refrigerants. The GWPs of R-1234yf and R-1234ze(E) are 4 and 6, respectively, far below that of R-410A (US EPA, 2010a; IPCC-AR4, 2007). Both of these alternative refrigerants are slightly flammable, a property not exhibited by chlorofluorocarbons like R-22 and some fluoroalkanes (*e.g.*, R-125). R-32, another slightly flammable refrigerant, was also included in the risk assessment because it has not been used previously by itself in residential heat pump applications. The GWP of R-32 is 675 (US EPA, 2010b).

Table 2.1 summarizes the flammability properties of the refrigerants under study along with flammability properties for two other flammable gases which have also been used as refrigerants: propane and ammonia. Testing according to ASTM E-681-04 indicates R-1234yf is flammable at room temperature (*i.e.*, 21°C, 70°F)[2], with a lower flammable limit (LFL) of 6.2% and an upper flammable limit (UFL) of 12.3% (DuPont, 2011). R-1234ze(E) is not flammable at normal room temperature but does become flammable at temperatures above 30°C (86°F). In this temperature range, the LFL is 7.0% and the UFL is 9.5% (Honeywell, 2008a). R-32 is flammable at room temperature although the flammable concentration range is substantially higher than that of R-1234yf, with an LFL of 14.4% and a UFL of 29.3% (Minor and Spatz, 2008). However, on a mass basis, R-1234yf and R-32 have similar LFLs: 0.29 and 0.31 kg/m^3 (0.018 and 0.019 lb/ft^3), respectively. All three refrigerants have high ignition energies; tests conducted at DuPont using an electrical spark as an ignition source showed that the minimum ignition energy (MIE) for R-1234yf was between 5,000 mJ and 10,000 mJ (Minor and Spatz, 2008), and the MIE of R-1234ze(E) was reported to be between 61,000 and 64,000 mJ when tested at 54°C (129°F) (Spatz, 2008). The MIE of R-32 is between 30 and 100 mJ (Minor and Spatz, 2008). For comparison, the MIE of propane and gasoline vapor are both below 1 mJ and the spark energy of common spark plugs is in the range of 20 to 30 mJ (ACC, 2007). Thus, it would take a substantial ignition source (a very high energy spark, an open flame, or a very hot surface) to ignite these three candidate refrigerants.

Even if ignited, 2L refrigerants pose a limited risk of fire due to their low burning velocities. By definition, 2L refrigerants have a measured burning velocity less than 10 cm/s (0.3 ft/s). The burning velocity of R-1234yf is 1.5 cm/s (0.05 ft/s) (Minor and Spatz, 2008) and, because it is not flammable at temperatures below 30°C, the burning velocity of R-1234ze(E) is by definition zero. The low burning velocities of R-1234yf and R-1234ze(E) suggest that even if they are ignited, the flame could be extinguished by wind or drafts moving at fairly minimal speeds. The burning velocity of R-32 is higher, 6.7 cm/s (0.22 ft/s), but still well below that of flammable gases such as propane (46 cm/s) (Minor and Spatz, 2008).

The toxicity of the three refrigerants has also been evaluated extensively in animal studies. All three refrigerants display low acute toxicity, low chronic toxicity, a high anesthetic threshold, and no potential for inducing cardiac sensitization (a toxicological property of concern for many other refrigerants). All are assigned to ASHRAE toxicity classification A (lower toxicity). The workplace occupational exposure limits for these refrigerants are fairly high, further indicating a low risk from repeated exposure. Based

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[2] SI or SI-derived units and their standard abbreviations are used throughout this document. In cases where non-SI units are commonly used (*e.g.*, length or temperature), the relevant conversion is given the first time a value appears in the text.

on the low toxicity of all three refrigerants, the critical concern for risk assessment is therefore the potential for refrigerant ignition. Table 2.2 summarizes the toxicological properties of the refrigerants under study along with those of R-410A and R-22, the refrigerants currently used in residential air conditioning and heat pumps.

Table 2.1 Flammability Characteristics of Refrigerants Under Study and Comparison Chemicals

Property	R-1234yf	R-1234ze(E)	R-32	Propane	Ammonia
Lower Flammable Limit (% volume in air)	6.2	7(1)	14.4	2.2	15
Upper Flammable Limit (% volume in air)	12.3	9.5(1)	29.3	10	28
Minimum Ignition Energy (mJ)	>5000, <10,000	61,000 - 64,000(2)	>30, <100	0.25	100-300
Burning velocity (cm/s)	1.5	0(3)	6.7	46	7.2
ASHRAE Safety Classification(4)	2L	2L	2L	3	2L

Notes:
All data taken from Minor and Spatz (2008) unless otherwise indicated.
1 R-1234ze(E) is not flammable at ambient temperatures; the data shown were obtained at 30°C.
2 R-1234ze(E) is not flammable at ambient temperatures; the data shown were obtained at 54°C.
3 Cannot be measured (*i.e.*, non-flammable) in the standard test.
4 ASHRAE Standard 34.

Table 2.2 Toxicity Data for Refrigerants Under Study and Comparison Chemicals(1)

Endpoint	R-1234yf	R-1234ze(E)	R-32	R-410A(5)	R-22
Acute (LC50) (ppm)	>406,000	>207,000	>760,000	763,000	220,000
Anesthetic Effects (ppm)	201,000	>207,000	250,000	311,000	140,000
Cardiac Sensitization No Effect Level (ppm)	>120,000	>120,000	>200,000	133,000	50,000(7)
Worker Exposure Limit (ppm)	500(2)	800(3)	1,000(4)	1,000(6)	1,000(8)
90-day NOAEL (ppm)	50,000(2)	5,000(3)	50,000(4)	50,000(6)	10,000(8)
Genotoxicity	Negative(2)	Negative(3)	Negative(4)	Negative(6)	Negative(8)
ASHRAE ATEL (ppm)	101,000	59,000	200,00	133,000	59,000

Notes:
(1) Taken from Table E-1, ASHRAE Standard 34 (ASHRAE, 2010) unless otherwise noted.
(2) DuPont, 2011; Minor and Spatz, 2008.
(3) Honeywell, 2008b.
(4) ECETOC, 2008.
(5) Estimated based on the properties of R-32 and R-125 and the mole fraction of each in the blend.
(6) Kawano *et al.*, 1995.
(7) Lowest effect level.
(8) National Refrigerants, 2008.
> Effect was not observed at the highest concentration tested.
LC50 = lethal concentration, 50 percent
NOAEL = no observed adverse effect level
ppm = parts per million

3 Data Acquisition

3.1 Consideration of Hazard Scenarios to be Addressed

A critical stage of the risk assessment is to identify those scenarios in which an ignition source is present in conjunction with a flammable concentration of leaked refrigerant. To better understand these scenarios, one must consider the various triggering events which could cause refrigerant to be released, the location of the release, and the specific type of person that might be present. It is important to note that during normal operations, the refrigerant will be contained within the residential heat pump system and thus there is no risk of adverse events associated with these refrigerants during regular use. However, if a refrigerant leaks from the equipment and is not dispersed prior to accumulating to a flammable concentration and a sufficient energy source is present, refrigerant ignition could occur. Based on available data and detailed discussions with AHRI project monitoring subcommittee members, a number of scenarios were developed for evaluation. The scenarios, which are similar to those assessed by Goetzler *et al.* (1998), are summarized below.

1. A leak occurring in a heat pump system while the unit is *idle*. The leak could occur in either the inlet piping or the air handler and could be due to an improperly brazed joint or equipment fatigue. The system could be located in one of four possible locations – an attic, basement, garage, or utility closet – and, in the event of a leak, the refrigerant could accumulate in these surrounding rooms. It was assumed that if the unit is operating (*i.e.*, blower on), the leaked refrigerant would be drawn into the ducts and blown into a downstream room (see #3 below).
2. A leak occurring in the outside portion of the split heat pump system. This could occur as a result of a part failure (*e.g.*, a feed-through plug or other part).
3. A leak occurring in a heat pump system while the unit is operating (*i.e.*, blower on). With the blower on, the refrigerant could be blown through the duct into a downstream room where an ignition source could be located.
4. A leak occurring in the air handler while the unit is idle and prior to it being turned on. In such a case, the refrigerant could accumulate to a flammable concentration in the air handler itself. If a heating coil or some other potential ignition source (*e.g.*, an electrostatic air cleaner) becomes active before the refrigerant dissipates, the refrigerant could be ignited.
5. A leak occurring while the system is idle with the refrigerant diffusing back through the return air ductwork (*i.e.*, the refrigerant would leak into the room supplying the return air).
6. A leak occurring inside a wall due to rupture of refrigerant piping within the wall. Such a leak could be due to human error (*e.g.*, home construction activity).
7. A leak occurring during system repair. This could occur either as a result of improper recovery or recharging of refrigerant during work or due to faulty procedures used to test for a pre-existing leak (*e.g.*, a propane torch).

Note that a leak event by itself is not sufficient to produce refrigerant ignition. The leak must be large enough to produce flammable concentrations in the location of concern, and a sufficient ignition source must be present at the same time and location as the flammable concentration of gas. We conducted both modeling and measurement studies, as described in the following section, to address the question of whether flammable concentrations can be produced from refrigerant leaks.

3.2 Computational Fluid Dynamics Modeling

To support the risk assessment, we conducted air dispersion modeling to determine whether leaked refrigerant would attain flammable concentrations in rooms where heat pump units (*i.e.*, air handlers and associated piping) might be located. Such information is informative for scenarios 1 and 7 identified above, which were among the most significant scenarios in the Goetzler *et al*. (1998) study and were considered appropriate for additional exploration.[3]

The indoor dispersion of a refrigerant leak varies depending upon the characteristics of the space where the leak occurs – namely, the dimensions of the space, the presence of objects (walls, furniture, other objects), the size of the air flow connections between various rooms, and the degree of air exchange. The effect of these factors on dispersion of a leaked gas can be determined *via* computational fluid dynamics (CFD) modeling. GexCon (Baltimore, MD) used its proprietary CFD software, FLACS, to carry out the modeling. FLACS has been used extensively for modeling gas dispersion and explosion potential within many industries. Like other CFD modeling programs, FLACS divides the airspace within the simulation environment into many small cells and uses the properties of the material in question and various environmental variables (air flows, temperatures, surface roughness of objects) to estimate the transfer of gas between adjacent cells over time. For the purpose of this study, GexCon built a virtual generic residential unit consisting of a 200 m^2 (2,150 ft^2) two-story house with a basement and attached garage (Figure 3.1). Appropriate furniture was place in the house to create realistic air volumes in each room. Air flow between rooms was passive (*i.e.*, HVAC system off) and driven largely by the air currents generated by the refrigerant releases.

GexCon conducted a large number of different simulations involving different conditions. Simulations included large releases of R-32 (146 to 170 g/s, 19.3 to 22.5 lb/min) and R-1234ze(E) (78 to 96 g/s, 10.3 to 12.7 lb/min) in the four locations where the indoor section of a split system heat pump might be located (*i.e.*, attic, basement, garage, and utility closet). Simulations were initially run at release rates of 170 g/s and 78 g/s for R-32 and R-1234ze(E), respectively, and then were later rerun using the actual release rates attained in the experimental study described below. The refrigerant was released from a height of 0.6 m (24 in) from the floor, consistent with a leak from a ruptured tube of an indoor unit. The exception to this was the attic release scenario, where the release was at a height of 0.15 m (6 in) to account for the horizontal alignment of the unit in an attic installation. Initial simulations for R-1234yf (for the basement and utility closet) indicated nearly identical results compared to those for R-1234ze(E), so the latter refrigerant was used for all remaining simulations. Two utility closet sub-scenarios were also considered: one with the utility closet door closed (resulting in maximum concentrations in the utility closet) and one with the utility closet door open (resulting in maximum concentration in the adjoining kitchen). The charge size used in all large release simulations was 3.4 kg (7.5 lb). The use of equal charge levels for R-32 and R-1234yf/ze(E) was an assumption; charge levels of actual systems will depend on system design. For comparable efficiency, capacity and heat exchange technology, a lower pressure refrigerant will likely have a higher charge level than a high pressure refrigerant.

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[3] Scenario 2, involving a refrigerant release in the outdoor portion of the unit, was also a risk driver for Goetzler *et al*., but the probability of the refrigerant attaining a flammable concentration in this location depends on wind conditions. If wind air currents are present, the refrigerant will be dispersed prior to reaching the LFL; if wind air currents are absent, it can be assumed the refrigerants will reach the LFL for at least a short period of time. CFD modeling would provide little information for this scenario.

Beyond the initial large release scenarios, GexCon evaluated refrigerant dispersion after small (1.5 g/s) and very small (0.15 g/s) releases of R-1234ze(E) in the utility closet and basement, as well as a smaller (1.5 g/s) R-32 release in the utility closet involving a sixty percent larger charge of refrigerant (*i.e.*, 5.45 kg, 12 lb). All simulations were run until refrigerant concentrations reached an asymptote.

The CFD modeling provided two types of output: (1) video simulations of refrigerant release and dispersion over time with color coding indicating approximate refrigerant concentrations in the space, and (2) more exact concentration data at specific points in each room (Table 3.1). The former provides a better estimation of refrigerant concentration spatially, although the precision is limited; the latter provides a more exact estimate of refrigerant concentration but only at certain points, which may not coincide with the maximum concentration location. For the videos, refrigerant concentrations were predicted at the 0.15 and 0.6 m heights, which were considered consistent with heights at which ignition sources (*e.g.*, heaters, electrical wiring) could be present. Exact concentrations were tracked at up to seven variable height locations in each scenario where specific ignition sources might be located (*e.g.*, water heater heat sources near the floor, wall sockets, countertop appliances, individuals lighting a cigarette).

Tables 3.2 to 3.4 summarize the results of the testing, and plots of refrigerant concentration over time for each scenario are shown in Figures 3.2 through 3.18. More detail concerning the CFD modeling is provided in Appendix A. As noted above, initial simulations indicated that the dispersion pattern of R-1234yf and R-1234ze(E) was nearly identical (see for example, Figures 3.3 and 3.4), providing support for conducting the remaining simulations on only one compound.

In the utility closet scenarios, R-32 concentrations exceeded 14% (*i.e.*, the LFL of R-32) whether or not the closet door was closed; however, a larger portion of the utility closet had concentrations above the LFL when the closet door was closed (Figure 3.19). The duration of time the refrigerant was in the flammable concentration range also differed: approximately 70 s with the door closed and less than 20 s with the door open. When the utility closet door was closed, R-32 concentrations were in the flammable concentration range in a small part of the kitchen immediately adjacent to the utility closet, but only for approximately 10 s. Concentrations in the rest of the kitchen, including at the monitoring points identified as likely locations for potential ignition sources, were all below the flammable range.

Visual examination of the video simulations for R-1234yf and R-1234ze(E) indicates that, with the utility closet door <u>closed</u>, concentrations of these refrigerants exceeded 7% (*i.e.*, exceeded the LFL of both refrigerants). The time above the LFL was approximately 45 s for R-1234ze(E) and 65 s for R-1234yf (because the LFL for R-1234yf is lower). Concentration predictions at the specific monitoring points indicated a peak concentration in the utility closet of 7% for R-1234ze(E) (*i.e.*, just at the LFL) and 6.8% for R-1234yf.[4] Both also exceeded the LFL briefly in a small area of the kitchen near the door but only at 0.15 m. The duration of this exceedance was approximately 5 s for R-1234ze(E) and approximately 40 s for R-1234yf. When the simulation was run with the utility closet door open, the simulation videos indicated that R-1234ze(E) and R-1234yf each reached the LFL briefly in the area around the leak in the utility closet at 0.15 m (for approximately 15 and 20 s, respectively), although this was not seen with the specific monitoring point data (maximum concentration 4.8%).

In the remaining scenarios (those involving the attic, basement, and garage), neither R-32 nor R-1234ze(E) produced concentrations exceeding the LFL with the exception of the area immediately in front of the leak, a narrow cylinder approximately 0.76 m (2.5 ft) in length (Figure 3.20). In each of these simulated scenarios, the refrigerant beyond the immediate vicinity of the leak quickly mixed with the room air and reached uniform and low concentrations.

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[4] The time that R-1234ze(E) is at 7% is less than 1 s, indicating the two results are more similar than they may appear.

For R-1234ze(E), GexCon also conducted simulations with smaller leak rates (1.5 g/s and 0.15 g/s) because prior studies using R-32 indicated that slower leaks (*i.e.*, approximately 1 g/s) allowed for greater accumulation of refrigerant in a particular area such that the LFL could be exceeded (Goetzler *et al.*, 1998). This was not observed with R-1234ze(E). In both of the simulations (1.5 g/s and 0.15 g/s leaks), the refrigerant quickly mixed with room air and the concentration was always below 2%. Thus, for R-1234ze(E) (and presumably R-1234yf, as it exhibits similar properties), these slower leaks did not present a credible ignition possibility. The final simulation, which examined a 1.5 g/s leak of R-32 in the utility closet (door closed) with a 5.45 kg charge of refrigerant, also indicated a negligible ignition possibility. The concentration of R-32 in the utility closet never exceeded 5%, with the exception of the area immediately in front of the leak (a narrow cylinder approximately 0.76 m in length).

Overall, the CFD modeling indicates an R-32 ignition possibility in the utility closet scenario (whether the door is open or closed) when the leak is very large (170 g/s), but it does not pose a refrigerant ignition possibility in the other three locations considered because the refrigerant is rapidly diluted in room air. The only area where the LFL is exceeded in these cases occurs directly in front of the leak. This constitutes a very small volume relative to the total volume considered. A smaller R-32 leak (1.5 g/s), even with a higher charge mass, did not produce flammable concentrations in the utility closet space. With respect to R-1234yf and R-1234ze(E), the CFD modeling demonstrated that flammable concentrations were produced in the utility closet when the utility closet door was closed in the event of a large refrigerant leak (78 g/s). The LFL was either approached or reached (albeit very briefly) at the 0.15 m height with R-1234yf and R-1234ze(E) when the utility closet door was open based on the video simulation. This was not confirmed, however, by the specific monitoring point data. R-1234ze(E) did not exceed the LFL when the door was closed and the leak was smaller (1.5 g/s or 0.15 g/s). Modeling also indicated that a large R-1234ze(E) leak (94 to 96 g/s, 12.4 to 12.7 lb/min) in the basement, garage, and attic scenarios did not produce concentrations above the LFL, except for a very limited area immediately in front of the leak. It should be noted that the low burning velocity of these refrigerants make it questionable whether a flame even in this small area could be sustained given the turbulent air flow associated with the leak.

3.3 Experimental Study/Concentration Measurements

Hughes Associates (Baltimore, MD) conducted experimental testing to validate the results of the CFD modeling. To evaluate releases in the four main location scenarios (attic, basement, garage, and utility closet), Hughes constructed a mock–up of the first floor of a residential building. The area of the entire mock-up was 100 m^2 (1,076 ft^2) and the footprints of the individual rooms were constructed to be consistent with those used in the CFD modeling (Figure 3.22). The second floor of the house (where no refrigerant release was intended) was not included in the mock-up, because it was considered extremely unlikely that refrigerant would reach the second story at measureable levels from a first floor release (this was subsequently observed to be the case). The mock-up was constructed with wood framing and 16 mm (5/8 in) sheetrock, and it included an 2.4 m (8 ft) high acoustic tile ceiling and a steel plate floor (with joints taped). The mock-up was entirely located within an existing building at Hughes, and thus it was not subject to wind or other external air flow effects. Testing was conducted with passive air flow only (aside from that generated by the release), simulating an HVAC "blower–off" condition. This represented an extreme situation in terms of minimizing refrigerant dispersion. Cardboard boxes, stacked and placed next to one another, were used to simulate the volumes occupied by counters, appliances, a vehicle, and the air handler itself (Figure 3.22).

In each test, a refrigerant charge 3.4 kg, the same as used in the CFD modeling) was released from the same location used in the CFD modeling. The refrigerant was released from a nominal 12L cylinder *via*

9.5 mm (3/8") copper tubing. The length of the tubing from cylinder to discharge point was approximately 30 m (98.4 ft). Due to a wide variation in system design, as well as the difficulty in transporting and setting up an actual heat pump system, a simulated release from a consistent release point was judged to be more suitable for experimental testing.

Releases were conducted only with R-1234ze(E) and R-32. Because R-1234ze(E) and R-1234yf have nearly identical vapor densities and diffusion coefficients, it was decided to conduct tests only with R-1234ze(E) and avoid doing tests that would provide essentially repetitive information (the appropriateness of this decision is supported by the results of the CFD modeling discussed above). Lubricant oil was not included in the cylinders. Oil would interfere with the gas sensor equipment, potentially leading to faulty readings. Because the oil represents a small mass relative to the total mass of refrigerant, it would not be expected to have a notable impact on refrigerant dispersion. Under actual conditions, some refrigerant may in fact remain in the heat pump system dissolved in the oil and, thus, would not contribute to air concentrations in the surrounding room. Prior to the release, the cylinder of refrigerant was heated in a warm water bath (50°C, 122°C) to facilitate refrigerant release. The saturation pressure of the refrigerant was held until the contents were depleted during a release. The release occurred in 2 stages, an initial liquid release (assumed to be 90% of the release) and a subsequent vapor phase release. The release rate was then estimated by dividing 90% of the total mass released by the liquid phase release time, determined from the cylinder pressure trace with an inflexion representing liquid run-out taken as the end of this portion of the discharge. Release rates were set as to be similar to those from working systems based on information supplied by AHRI member companies. Across all of the experiments, the actual release rates for R-32 ranged from 146 to 170 g/s while those for R-1234ze(E) ranged from 78 to 96 g/s.

Refrigerant concentrations were measured at up to seven locations in each scenario using total hydrocarbon (THC) analyzers. The analyzer array consisted of a Tripoint Instruments Model 123 (provided by Hughes) capable of analyzing three separate air samples and a set of five Henze Houck Processmeetechnik/Analytick GmbH Sensors (provided by Honeywell). The THC analyzers were calibrated prior to testing using standards for each of the refrigerants to be measured. The THC analyzers use thermal conductivity properties of a gas to measure the concentration of the gas in air. An air stream is drawn from the sampling location through a 6-mm (0.24 in) polyethylene tube to the analyzer *via* a sampling pump with a flow rate of approximately 1 to 1.5 liters per min (0.035 to 0.053 cfm). The length of the sampling tubes was approximately 30 m, allowing for the location of all instrumentation outside of the structure, thus minimizing air currents. Sampling locations were chosen for each scenario considering the locations of possible ignition sources (*e.g.*, water heater heat sources near the floor, wall sockets, countertop appliances, an individual lighting a cigarette). The sampling locations were the same as those monitored in the corresponding CFD simulation.

A total of 10 refrigerant releases were conducted, one for each refrigerant (*i.e.*, R-1234ze(E) and R-32) in the attic, basement, garage, and utility closet scenarios, plus two additional R-1234ze(E) releases in the basement scenario to obtain data on test reproducibility. Note that Hughes only evaluated the utility closet scenario with the closet door open. This was because the open-door case was expected to provide more extensive data for validating the gas dispersion pattern predicted by the CFD modeling.

Table 3.5 summarizes the results of the experimental testing. The maximum refrigerant concentration did not exceed the LFL for R-32 or R-1234ze(E) in any of the tests.[5] R-32 concentrations were consistently higher than those of R-1234ze(E), and, as one would expect, the highest concentrations were observed closest to the leak location. Within 5 minutes from the time of release, refrigerant concentrations at all sampling points reached a plateau and then slowly moved towards a uniform mixing situation. In general, the refrigerant moved across the lower portion of the room away from the leak location with only limited

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[5] That is, the LFL for R-1234ze(E) at temperatures above 30°C.

lateral and vertical dispersion. Locations at breathing zone height (where, for example, an individual might produce a flame to light a cigarette) were generally at or below the detection limit. Greater detail concerning the work conducted at Hughes is provided in Appendix B.

Table 3.6 presents the results of reproducibility testing (*i.e.*, three R-1234ze(E) tests in the garage scenario under identical conditions) and indicates the data were reproducible, with relative standard deviations (RSD, *i.e.*, 100•sd/mean) typically less than twenty percent. An exception was the sampling location on the other side of the closed basement door (RSDs ranged from 30% to 36%). This sample location is characterized by a particularly constrained gas migration path (*i.e.*, under the door), and the large volume of the adjoining room into which the gas migrates means that even slight differences in air currents could have a substantial effect. Overall, the reproducibility data suggest that test-to-test variability had a limited impact on the concentrations measured in the experimental testing and the data are fairly robust.

3.4 Comparison of Modeled to Measured Values

Figures 3.23 to 3.30 show a comparison of the results of the CFD modeling to the concentrations measured by Hughes. The comparisons include the peak concentration and the concentrations measured at 120 and 600 s. Note that the y-axis for each refrigerant is scaled to that refrigerant's LFL, the ultimate metric of interest. Hughes did not conduct testing with R-1234yf, but the LFL for R-1234yf is shown on the graphs related to R-1234ze(E) because the results would be expected to be similar.

In general, the comparisons indicate good agreement between the two sets of data. In the utility closet scenario, the two sets of results are often within 1.5 concentration percent. Agreement is still better in the other scenarios, where the modeled and measured concentrations are typically within 1 concentration percent. The agreement is least consistent in the utility closet, where some sizeable differences do occur. Because the utility closet scenario involves a smaller space with more complex geometry (*i.e.*, proportionally greater volume of simulated obstacles, initial impingement of the jet on the opposite wall), the larger variation between the measured and modeled data is not surprising. For both R-32 and R-1234ze(E), the CFD modeling predicted higher peak concentrations at the sampling point in the utility closet (open-door scenario) than were actually measured during experimental testing (*e.g.*, peak CFD predicted R-32 concentration for 0.15 m high sample: 14.4%, measured peak concentration: 6.6%). It is possible that this was the result of using long (30 m) sampling lines to connect the sampling location to the analyzer, although a difference in values was not observed at other sample locations in the utility closet, basement, garage, or attic tests. The CFD results also suggest a more rapid settling of refrigerant compared to the data obtained during experimental measurement. That is, refrigerant concentration at higher elevations was predicted to decline more rapidly than was observed in the experimental testing. This is particularly noticeable at the 0.9 and 1.5 m (36 and 60 in) sample locations in the utility closet scenario. For example, R-32 concentrations at the 1.5 m height in the middle of the kitchen (utility closet scenario), were predicted to decline from 1.9% to 0.1% from the peak to the 5-minute time point. The corresponding experimental data showed a decline from 1.5% to 1.2%. A similar effect was also observed with the 1.5 m sample location in the garage, although the effect is less marked (CFD: 1.9% to 0.5% in 5 minutes; Measured: 1.5% to 1.45%). However, because the experimental and modeled refrigerant concentrations at higher elevations were consistently quite low (*i.e.*, less than 2%), this effect has little bearing on the question of potential refrigerant ignition. We also observed that the precision demonstrated between the modeled and measured data was poorer at low concentrations (around 1% or less); this may reflect limitations of the field sampling equipment. This is particularly notable in the comparison of R-1234ze(E) data in the attic release scenario (Figure 3.31) where the CFD predicted concentrations are all less than 0.5%. As indicated in this figure, the Hughes data do not show the expected decline in refrigerant concentration over time, which suggests a potential loss of analytical sensitivity at concentrations in this range.

Overall, given that the goal of this assessment was to determine whether the refrigerant concentration exceeds the LFL (*i.e.*, 6.2% for R-1234yf, 7% for R-1234ze(E) or 14.4% for R-32), the modest differences in concentration observed between the modeling results and experimental data suggest that the CFD modeling do provide a sufficiently accurate representation of actual experimental conditions.

Table 3.1 Monitoring Point Locations Used in CFD Modeling Simulations

Simulation Monitoring Point Location	Description	Height (m)	Height (in)
Main floor/Utility closet scenario			
1	Center of utility closet, just above floor	0.15	6
2	Outside utility closet door (in kitchen), just above floor	0.15	6
3	South kitchen wall, wall socket height	0.4	16
4	Center of kitchen, just above floor	0.15	6
5	East kitchen wall, counter top height	0.9	36
6	Center of kitchen, head height	1.5	60
7	Outside kitchen door in living/dining room, just above floor	0.15	6
8	North kitchen wall, counter top height	0.9	36
Basement scenario(1)			
1	1.5 m in front of leak, just above floor level	0.15	6
2	Near West wall, just above floor level	0.15	6
3	Near West wall, countertop appliance level	0.8	32
4	East of leak, towards washer/dryer mockup, just above floor level	0.15	6
5	Beyond closed basement utility room door, just above floor level	0.15	6
6	North wall (opposite leak), wall socket height	0.5	20
8	1.5 m in front of leak, head level	1.5	60
Garage scenario(1)			
1	West wall behind leak, middle height	0.8	32
2	North wall, counter top height	1.0	39
3	In front of leak, offset North by 0.7 m, just above floor	0.15	6
4	Center of garage, under vehicle	0.05	2
5	2.3 m in front of leak, just above floor level	0.15	6
6	In front of leak 0.6 m, just above floor	0.15	6
8	2.3 m in front of leak, head level	1.5	60
Attic scenario			
1	1 m in front of leak, just above floor	0.15	6
2	1 m in front of leak, possible work zone	0.6	24
3	Approximately 2 m West of location 1, just above floor	0.15	6
4	Approximately 2 m East of location 1, just above floor	0.15	6
5	2 m behind leak, just above floor	0.15	6
6	Approximately 3 m behind leak, just above floor	0.15	6
7	Behind leak, near kitchen door	0.15	6
8	Behind leak on opposite wall	0.15	6

Note: Locations are the same as those used in the experimental study conducted by Hughes Associates

1 Location 7 was not used in the basement and garage modeling because there was no corresponding location in the experimental study (due to sensor failure at the intended sample point). In order to keep the same numbering scheme between the two studies, location 7 was skipped and the final location was designated number 8.

Table 3.2 Results of CFD Modeling for R-32

Scenario (leak rate)	Maximum Conc. at 0.15 m (%)[1]	Time LFL Exceeded (s)	Maximum Conc. at Monitoring Points (%)[2]	Time LFL Exceeded (s)	Comment
Basic Scenarios					
Utility Closet, open door (170 g/s)	>14	<20	13.75	0	Based on a visual examination of the video simulation, at the 0.15 m height, R-32 exceeded the LFL in the utility closet and the kitchen area just past the utility closet door. R-32 did not exceed the LFL at any monitoring points in the utility closet or kitchen.
Utility Closet, closed door (170 g/s)	>14	70	16.5	60	Based on a visual examination of the video simulation as well as the specific monitoring point data, R-32 exceeded the LFL in the utility closet and, at 0.15 m, in a limited part of the kitchen door near the utility closet door.
Basement (159 g/s)	3	0	3.8	0	Concentrations well below the LFL in all locations.
Garage (146 g/s)	3	0	2.1	0	Concentrations well below the LFL in all locations.
Attic (146 g/s)	5	0	6.8	0	Concentrations well below the LFL in all locations.
Exploratory Scenarios					
Utility Closet, closed door, 5.45 kg charge (1.5 g/s)	5	0	4.3	0	Concentrations well below the LFL in all locations.

Notes:

1 Determined based on reviewing time course videos of the refrigerant release.

2 Determined by examining graphs of refrigerant concentration at the specified monitoring points over the course of the release.

LFL = lowest flammable limit.

All simulations run with a 3.4 kg system charge unless otherwise noted.

Table 3.3 Results of CFD Modeling for R-1234ze(E)

Scenario (leak rate)	Maximum Conc. at 0.15 m (%)[1]	Time LFL Exceeded (s)	Maximum Conc. at Monitoring Points (%)[2]	Time LFL Exceeded (s)	Comment
Basic Scenarios					
Utility Closet, open door (78 g/s)	7	15	4.8	0	Based on visual examination of the video simulation, R-1234ze(E) exceeded the LFL in the utility closet at the 0.15 m height only in the area immediately in front of the leak. The LFL was not reached in the adjoining kitchen. Evaluation of the specific monitoring point data did not indicate the LFL was reached.
Utility Closet, closed door (78 g/s)	8	45	7	0	Based on a visual examination of the video simulation, R-1234ze(E) exceeded the LFL in the utility closet and, at 0.15 m, in a limited part of the kitchen door near the utility closet door. R-1234ze(E) briefly (<1 s) reached the LFL in the utility closet based on the specific monitoring points.
Basement (94 g/s)	6	0	1.8	0	Concentrations well below the LFL in all locations.
Garage (96 g/s)	2	0	1.0	0	Concentrations well below the LFL in all locations.
Attic (96 g/s)	3	0	2.9	0	Concentrations well below the LFL in all locations.
Exploratory Scenarios					
Utility Closet, open door (1.5 g/s)	2	0	1.5	0	Concentrations well below the LFL in all locations.
Utility Closet, closed door (1.5 g/s)	<2	0	1.6	0	Concentrations well below the LFL in all locations.
Utility Closet, open door (0.15 g/s)	<2	0	0.4	0	Concentrations well below the LFL in all locations.
Utility Closet, closed door (0.15 g/s)	<2	0	0.5	0	Concentrations well below the LFL in all locations.
Basement (1.5 g/s)	2	0	1.9	0	Concentrations well below the LFL in all locations.
Basement (0.15 g/s)	<2	0	0.7	0	Concentrations well below the LFL in all locations.

Notes:

1 Determined based on reviewing time course videos of the refrigerant release.

2 Determined by examining graphs of refrigerant concentration at the specified monitoring points over the course of the release.

LFL = lowest flammable limit.

All simulations run with a 3.4 kg system charge.

Table 3.4 Results of CFD Modeling for R-1234yf[1]

Scenario (leak rate)	Maximum Conc. at 0.15 m (%)(1)	Time LFL Exceeded (s)	Maximum Conc. at Monitoring Points (%)(2)	Time LFL Exceeded (s)	Comment
Basic Scenarios					
Utility Closet, open door (78 g/s)	7	20	4.8	0	R-1234yf exceeded the LFL in a portion of the utility closet in the video simulations. This did not extend into the kitchen. R-1234yf did not exceed the LFL at any monitoring points in the utility closet or kitchen.
Utility Closet, closed door (78 g/s)	8	65	6.8	20	In the video simulations, R-1234yf exceeded the LFL in the utility closet at 0.15 and 0.6 m, and, at 0.15 m, in a limited part of the kitchen door near the utility closet door. With respect to the monitoring points, R-1234yf exceeded the LFL briefly in the utility closet but not in the kitchen.

Notes:

(1) Initial results indicated results for R-1234yf were nearly identical to those for R-1234ze(E) and therefore R-1234yf was not included beyond the initial utility closet simulations.

1 Determined based on reviewing time course videos of the refrigerant release.

2 Determined by examining graphs of refrigerant concentration at the specified monitoring points over the course of the release.

LFL = lowest flammable limit.

All simulations run with a 3.4 kg system charge.

Table 3.5 Concentration Data Obtained During Experimental Testing for Different Release Scenarios

Sampling Point	Sample Height (m)	Sample Height (in)	Possible Ignition Source	R-32		R-1234ze(E)	
				Maximum Conc. (%)	30 min TWA (%)	Maximum Conc. (%)	30 min TWA (%)
Utility Closet Scenario							
Utility Closet	0.15	6	Unshielded appliance pilot light	6.61	3.05	3.57	2.07
Outside Utility Closet	0.15	6	NA/dispersion	4.33	3.39	2.98	2.23
South Wall Socket	0.4	16	Wall socket short	2.65	1.81	1.57	1.01
Center Kitchen Low	0.15	6	NA/dispersion	4.76	3.74	2.96	2.35
East Wall Counter	0.9	36	Countertop appliance	4.20	2.59	2.50	1.10
Mid Kitchen High	1.5	60	Smoking-related source	1.54	0.99	0.25	0.01
Kitchen Wall - Countertop	0.8	32	Countertop appliance	2.30	2.02	1.35	0.85
Basement Scenario							
In Front of Leak	0.15	6	NA/dispersion	3.06	2.19	1.57	1.10
In Front and West of Leak [1.8 m]	0.15	6	NA/dispersion	3.26	2.32	1.56	1.2
In Front and West of Leak [1.8 m]	0.8	32	Countertop tools/appliances	1.79	0.89	0.77	0.35
In Front and East of Leak [4.5 m]	0.15	6	NA/dispersion	2.89	2.38	1.48	1.23
Basement Rec Room (behind door)	0.15	6	NA/dispersion	2.11	1.88	1.10	0.98
Behind Leak on Opposite Wall	0.5	20	Wall socket wiring short	2.88	1.03	1.73	0.54
In Front of Leak	1.5	60	Smoking-related source	1.7	0.99	0.98	0.59
Garage Scenario							
In Front of Leak	0.8	32	Countertop tools/appliances	2.49	2.18	1.21	1.05
North Wall - Countertop	1	39	Countertop tools/appliances	2.59	2.01	1.19	1.01
In Front of Leak - North	0.15	6	NA/dispersion	1.44	1.31	0.72	0.63
Center Room - Low	0.05	2	Underneath vehicle	2.77	2.39	1.42	1.22
In Front of Leak [0.6 m]	0.15	6	NA/dispersion	1.92	1.55	1.11	0.91
In Front of Leak [2.3 m]	0.15	6	NA/dispersion	3.02	2.56	1.45	1.26
In Front of Leak [2.3 m]	1.5	60	Smoking-related source	1.51	1.43	1.22	1.09
Attic Scenario							
In Front of Leak - Low	0.15	6	Wiring short	6.17	1.25	3.61	0.79
In Front of Leak - High	0.6	24	NA/dispersion	1.34	1.16	0.80	0.71
In Front of Leak - West	0.15	6	Wiring short	1.19	0.72	0.62	0.43
In Front of Leak - East	0.15	6	Wiring short	2.34	1.26	1.28	0.82
Behind Leak - [6.5 ft]	0.15	6	Wiring short	1.51	1.28	1.02	0.87
Behind Leak [10.5 ft]	0.15	6	Wiring short	0.96	0.63	0.62	0.50
Behind Leak - Right	0.15	6	Wiring short	0.00	0.00	0.00	0.01
Kitchen Wall - Behind Leak	0.15	6	Wiring short	1.89	1.21	1.10	0.92

Note: NA – No ignition source considered likely at this location; used primarily to understand dispersion of refrigerant.

Table 3.6 Reproducibility of Experimental Testing Results

Sample Description	Sample ID		Test 8	Test 9	Test 11	Mean	Std. Dev.	RSD (%)
In Front of Leak at Floor	1	Maximum	1.57	1.35	1.47	1.46	0.11	7.53
		5-min Average	1.27	1.16	1.27	1.23	0.06	5.15
		30-min Average	1.1	1.05	1.15	1.10	0.05	4.55
Left of Leak at Floor	2	Maximum	1.56	1.46	1.49	1.50	0.05	3.41
		5-min Average	1.32	1.2	1.29	1.27	0.06	4.92
		30-min Average	1.2	1.1	1.19	1.16	0.06	4.73
Left of Leak - High	3	Maximum	0.77	0.82	0.83	0.81	0.03	3.98
		5-min Average	0.66	0.65	0.7	0.67	0.03	3.95
		30-min Average	0.35	0.36	0.43	0.38	0.04	11.47
Far Side of Utility Area	4	Maximum	1.48	1.31	1.03	1.27	0.23	17.85
		5-min Average	1.26	1.11	0.88	1.08	0.19	17.67
		30-min Average	1.23	1.12	0.85	1.07	0.20	18.33
Outer Room, Beyond Closed Door	5	Maximum	1.1	1.02	0.59	0.90	0.27	30.36
		5-min Average	0.63	0.63	0.3	0.52	0.19	36.64
		30-min Average	0.98	0.88	0.46	0.77	0.28	35.68
Wall Opposite Leak at 0.9 m	6	Maximum	1.73	1.49	1.49	1.57	0.14	8.83
		5-min Average	0.91	0.98	1	0.96	0.05	4.91
		30-min Average	0.54	0.64	0.71	0.63	0.09	13.56
In Front of Leak - High	8	Maximum	0.98	0.86	0.98	0.94	0.07	7.37
		5-min Average	0.77	0.67	0.76	0.73	0.06	7.51
		30-min Average	0.59	0.55	0.48	0.54	0.06	10.31

Notes:

Data shown are repeat tests using R-1234ze(E) and the basement scenario set up.

Relative Standard Deviation (RSD) <10% is fairly good. The larger RSD in the outer room is not surprising given the small migration path (under the door) and the large room volume (even slight differences in air currents could be significant).

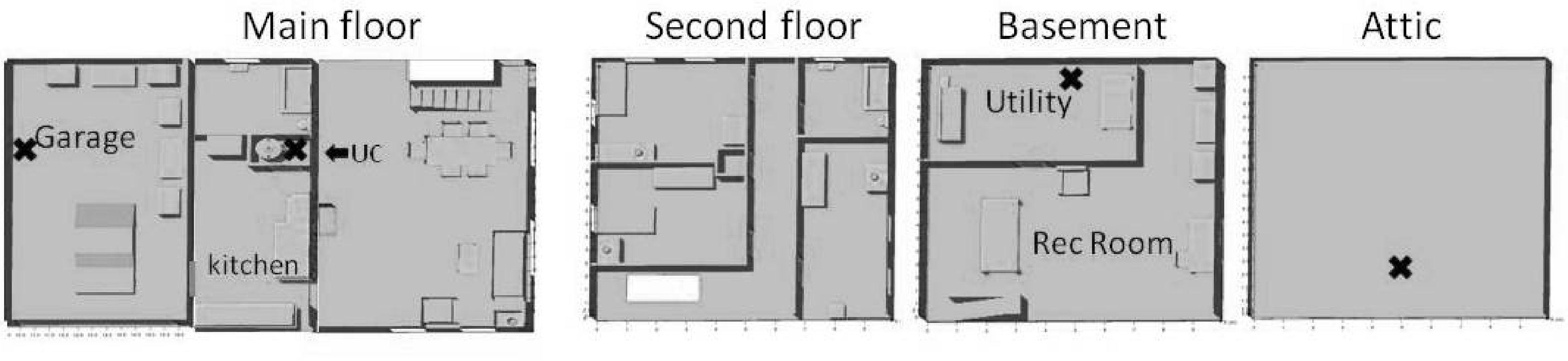


Figure 3.1 Schematic of House Model Used for CFD Modeling. The black x indicates the point of refrigerant release.

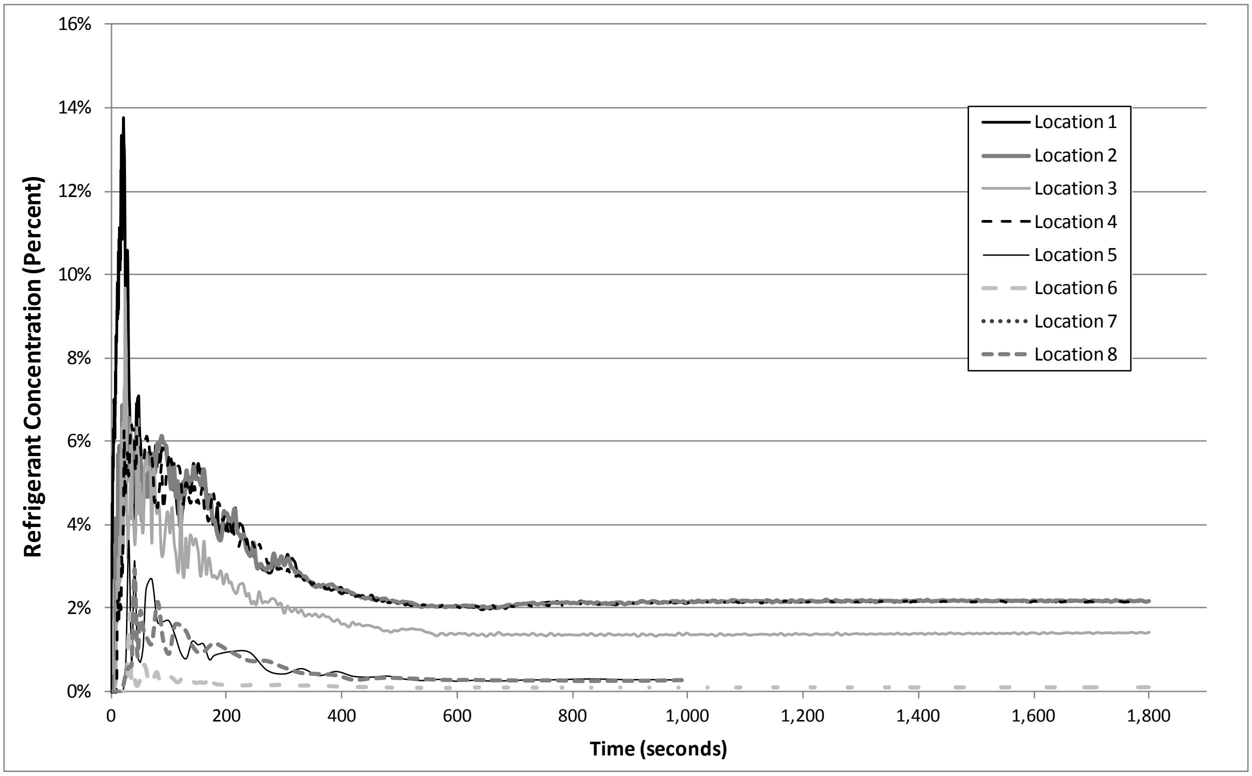


Figure 3.2 CFD-Predicted R-32 Concentrations for Utility Closet Release Scenario (Open Door)

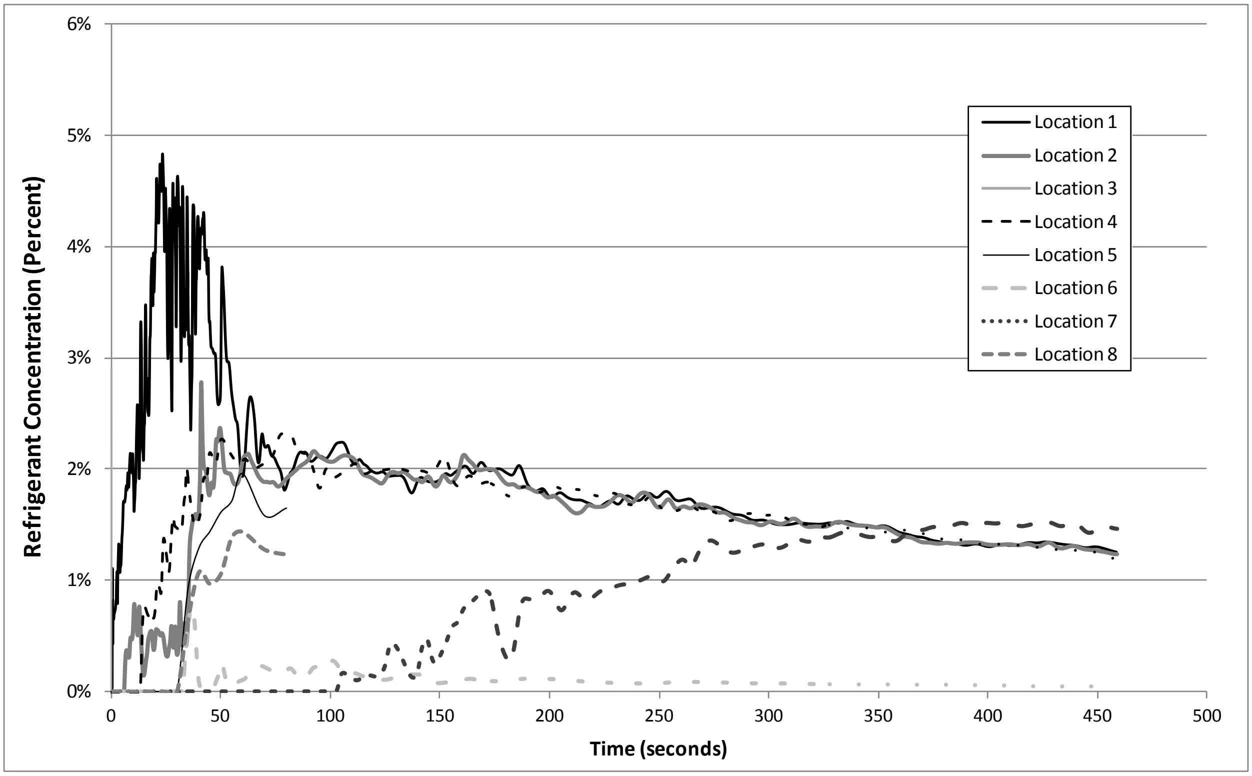


Figure 3.3 CFD-Predicted R-1234ze(E) Concentrations for Utility Closet Release Scenario (Open Door)

Note: Due to an error in sampling point specification for locations 5 and 8, data were extracted manually from the CFD model for these locations for the first 75 s. This includes the time of peak concentration.

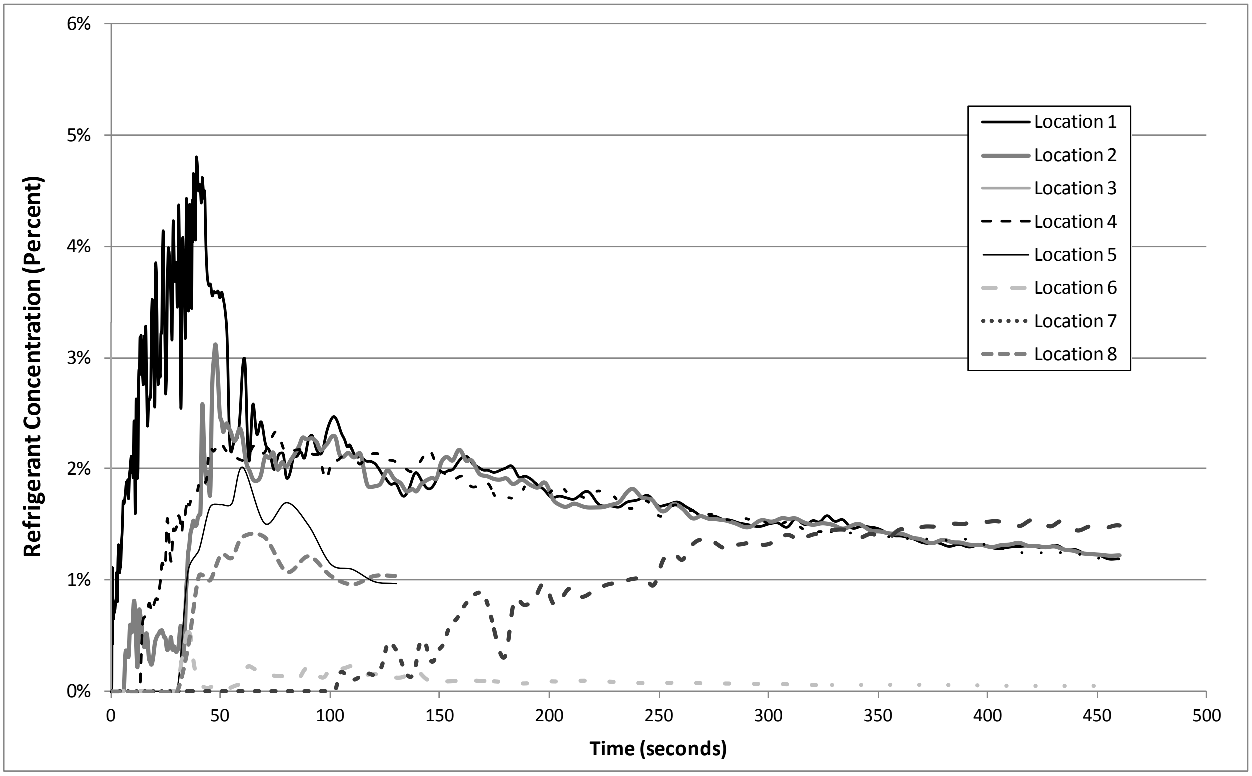


Figure 3.4 CFD-Predicted R-1234yf Concentrations for Utility Closet Release Scenario (Open Door)

Note: Due to an error in sampling point specification for locations 5 and 8, data were extracted manually from the CFD model for these locations for the first 125 s. This includes the time of peak concentration.

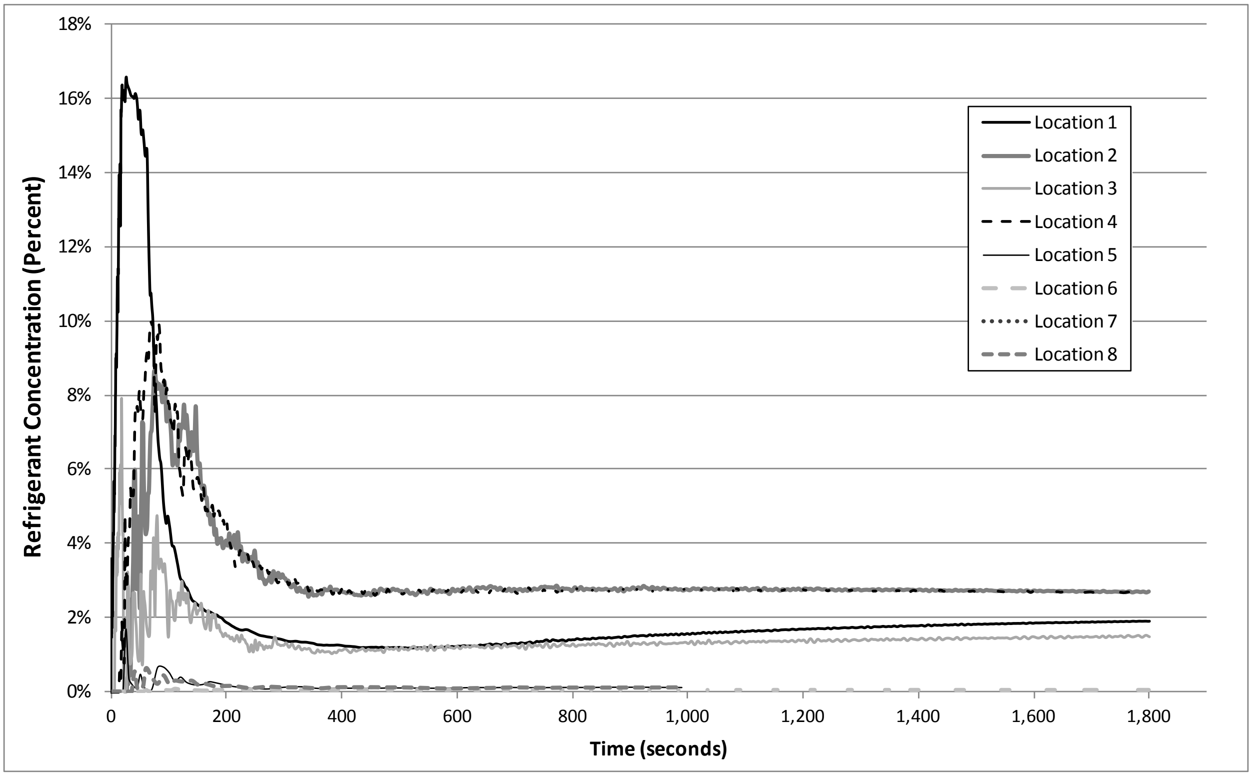


Figure 3.5 CFD-Predicted R-32 Concentrations for Utility Closet Release Scenario (Closed Door)

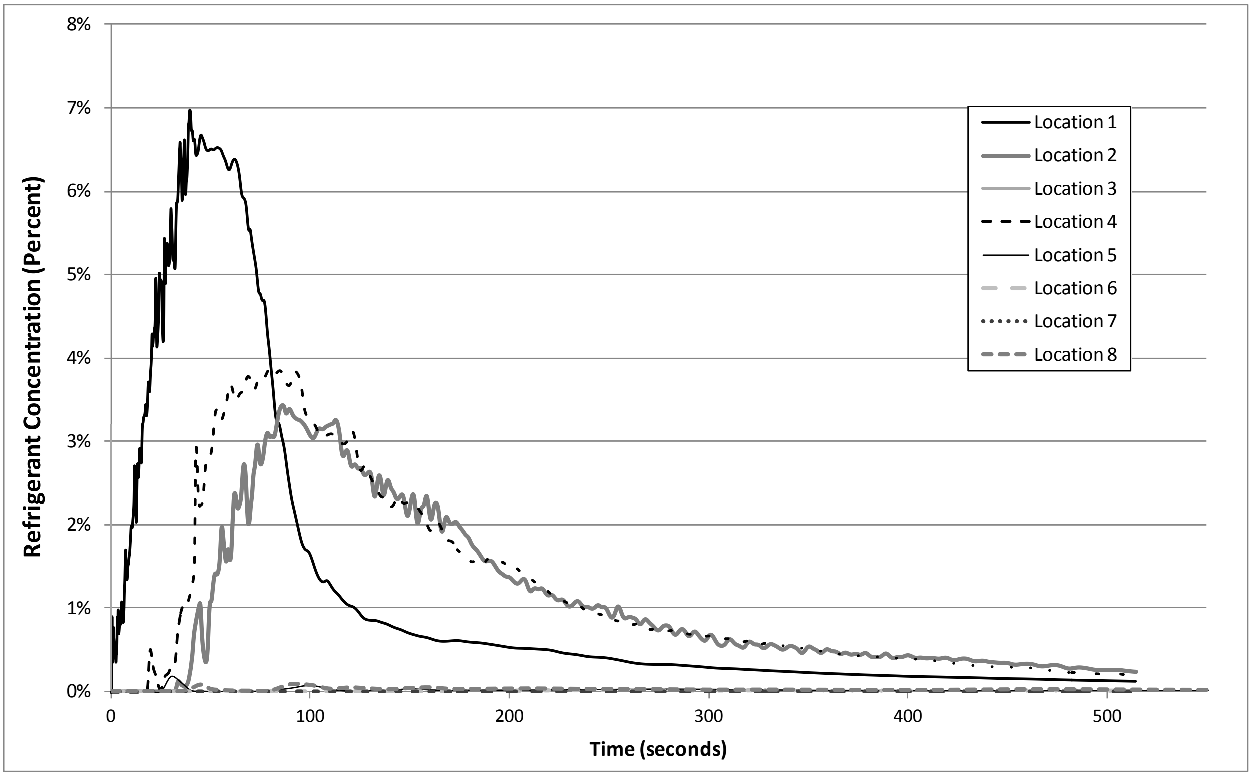


Figure 3.6 CFD-Predicted R-1234ze(E) Concentrations for Utility Closet Release Scenario (Closed Door)

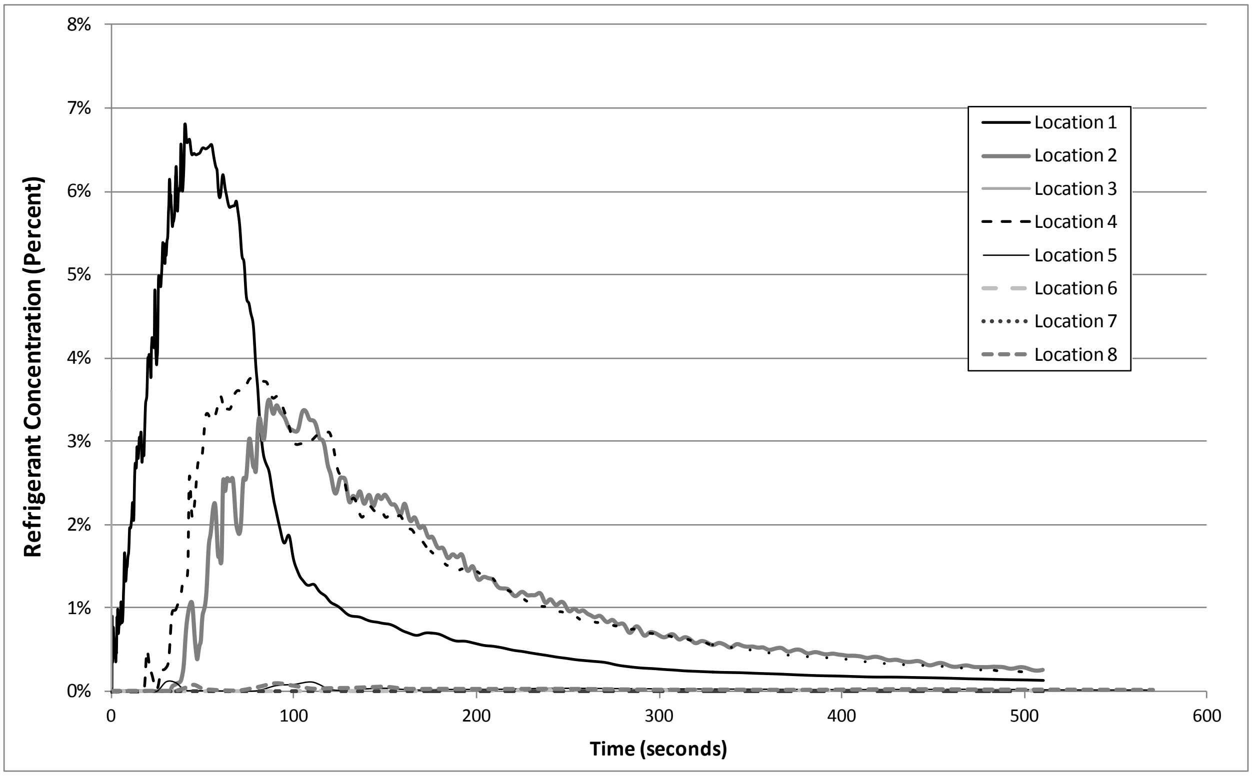


Figure 3.7 CFD-Predicted R-1234yf Concentrations for Utility Closet Release Scenario (Closed Door)

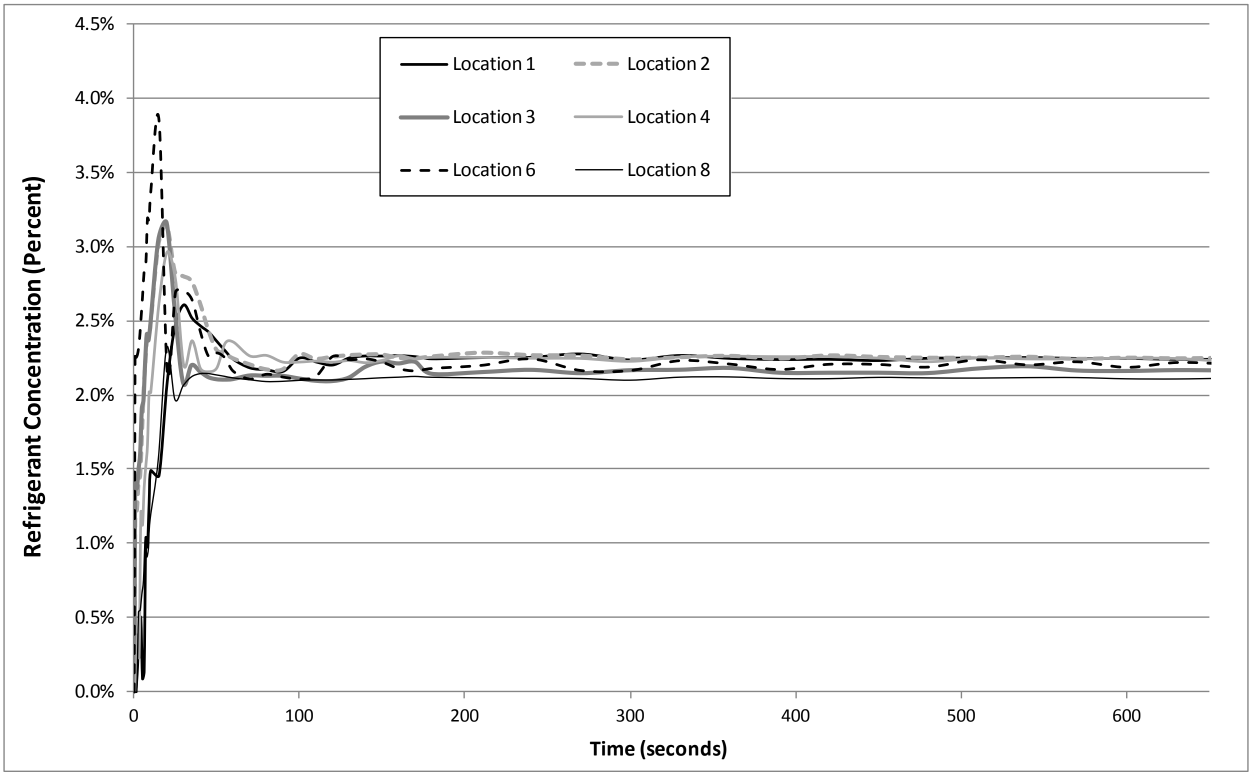


Figure 3.8 CFD-Predicted R-32 Concentrations for Basement Release Scenario

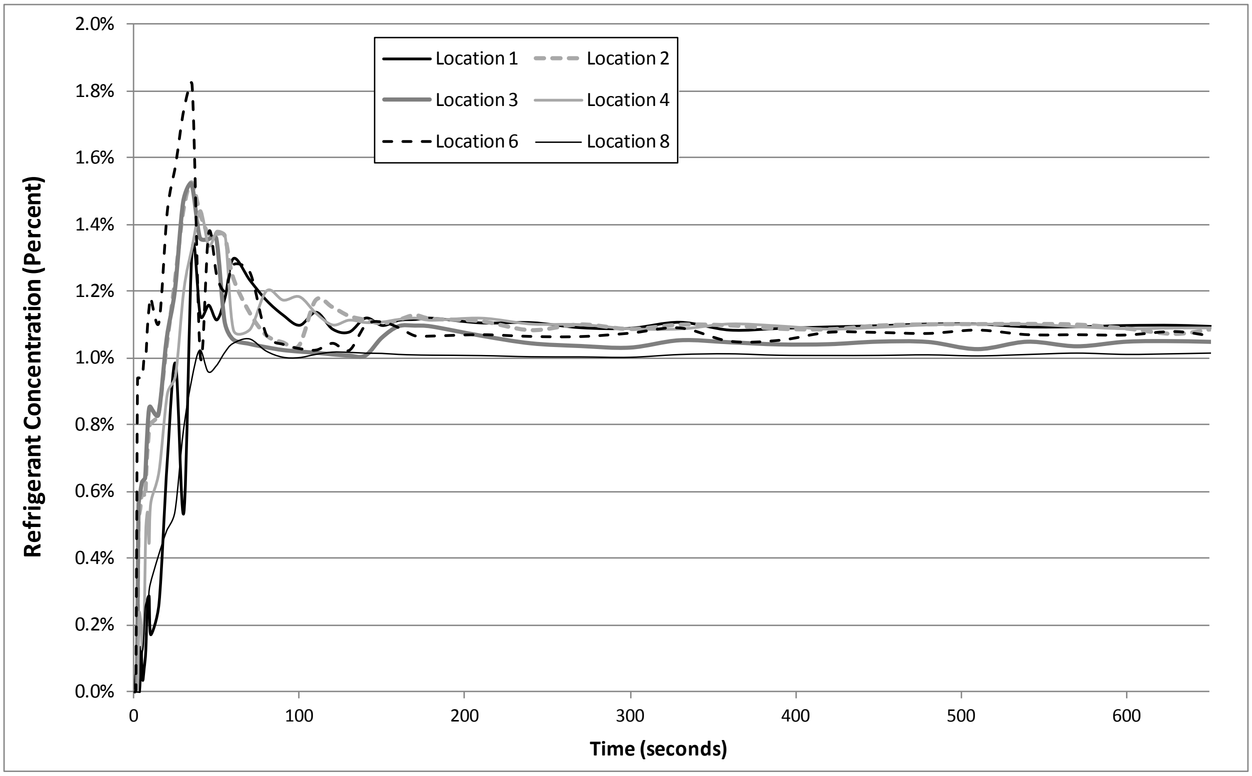


Figure 3.9 CFD-Predicted R-1234ze(E) Concentrations for Basement Release Scenario

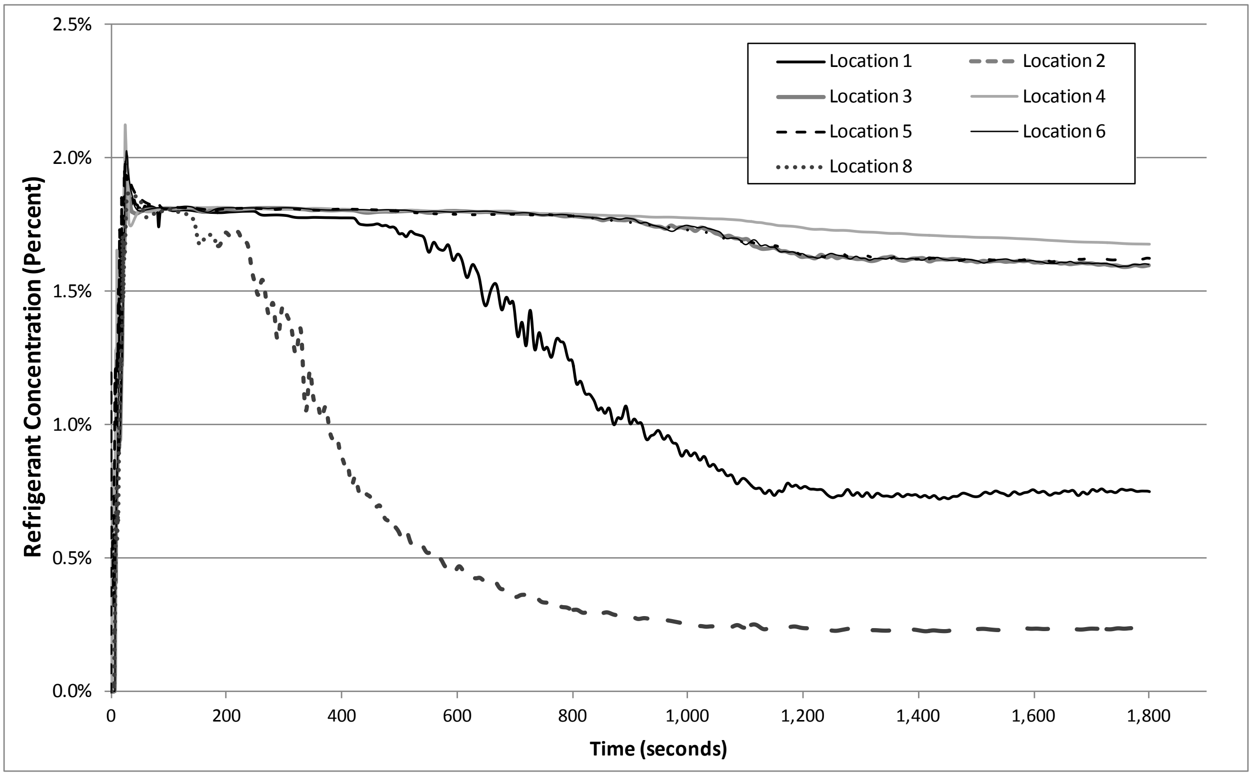


Figure 3.10 CFD-Predicted R-32 Concentrations for Garage Release Scenario

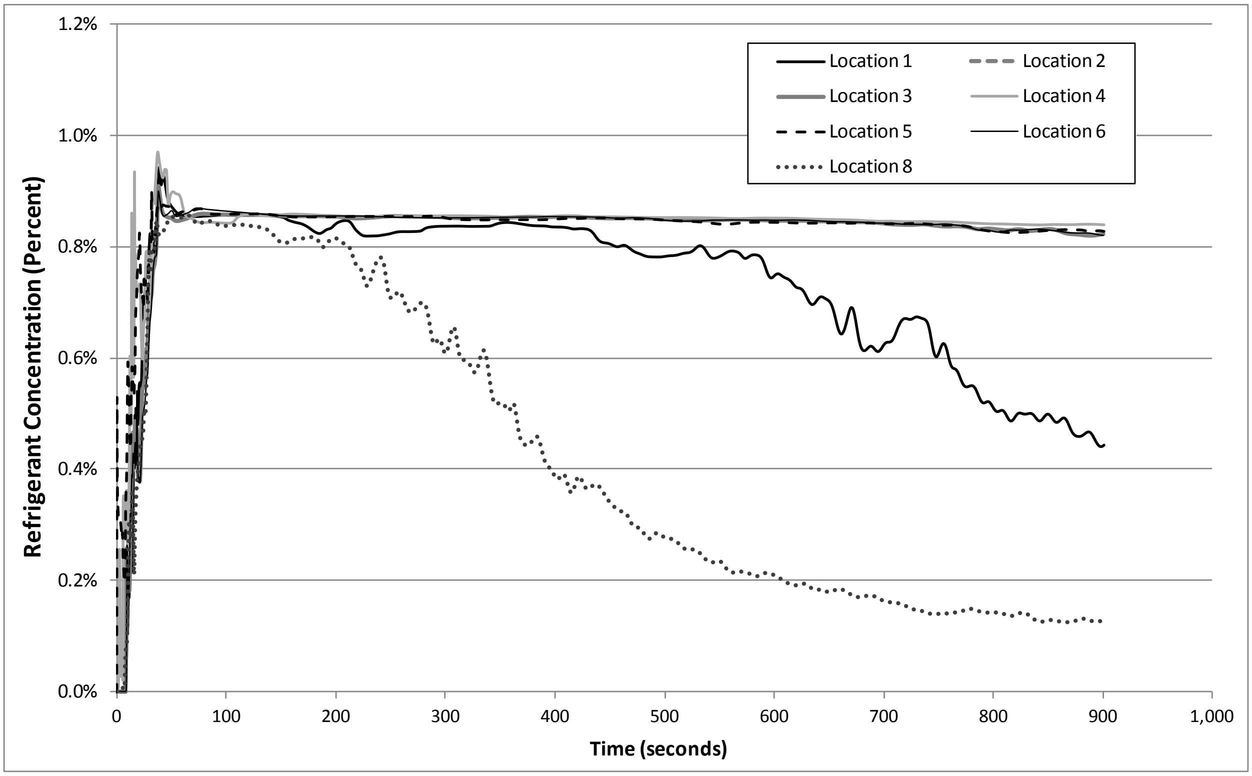


Figure 3.11 CFD-Predicted R-1234ze(E) Concentrations for Garage Release Scenario

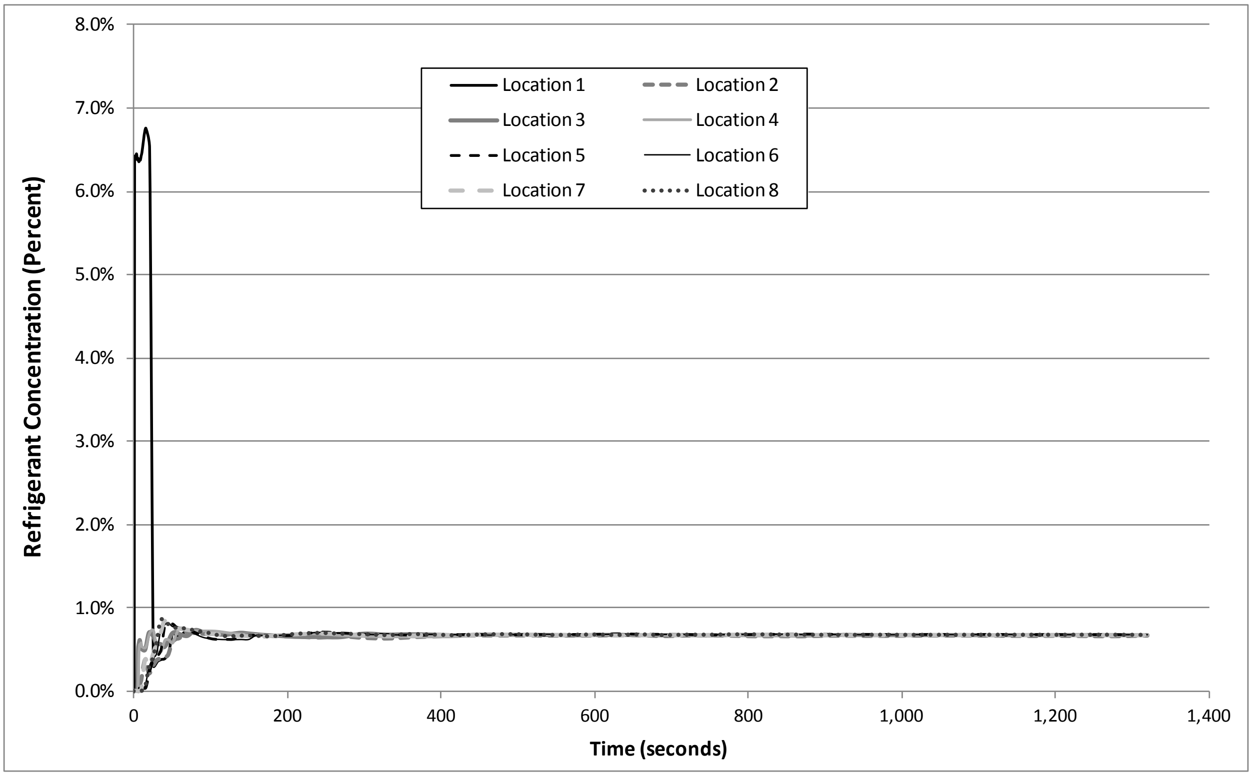


Figure 3.12 CFD-Predicted R-32 Concentrations for Attic Release Scenario

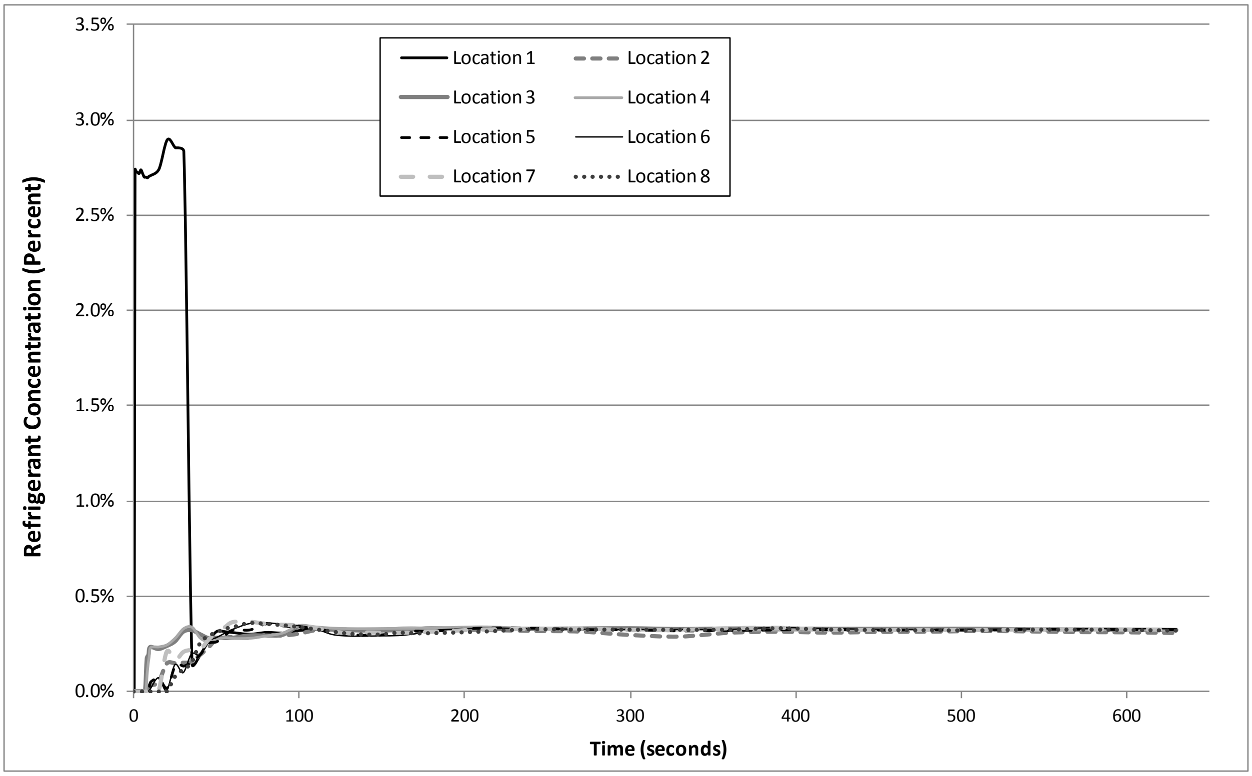


Figure 3.13 CFD-Predicted R-1234ze(E) Concentrations for Attic Release Scenario

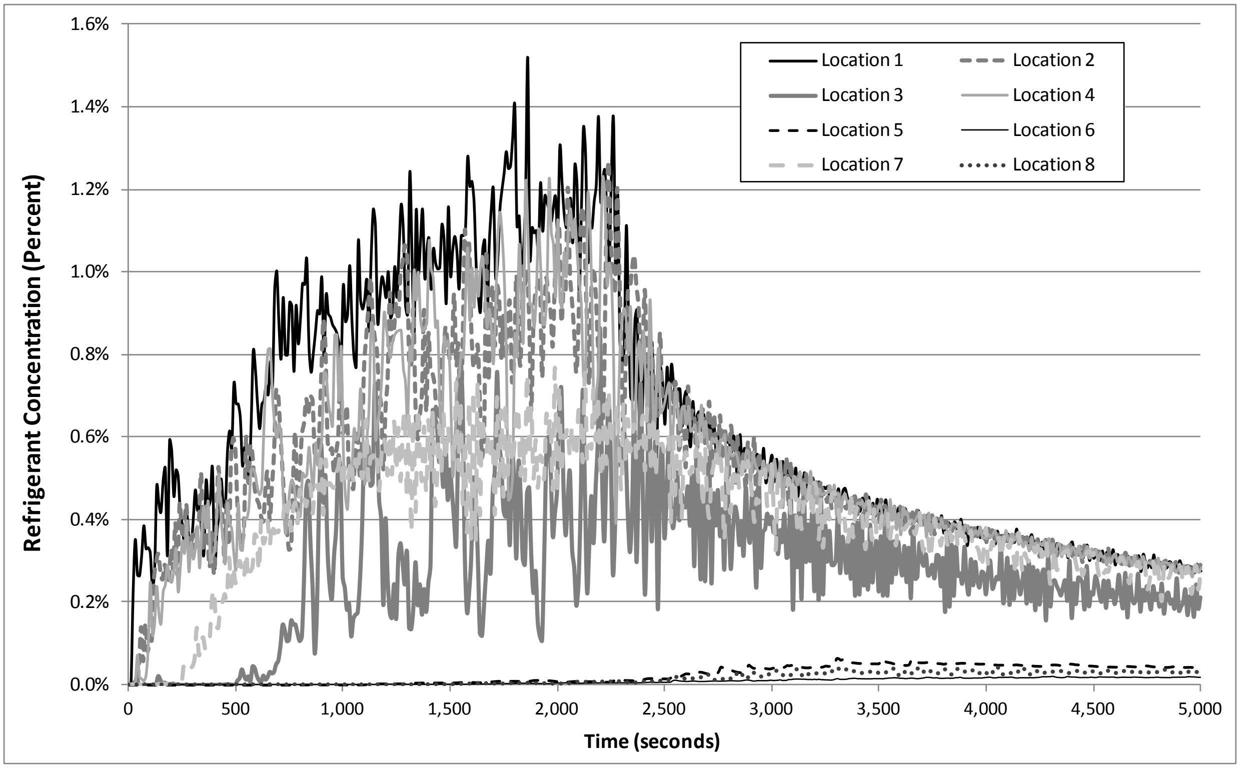


Figure 3.14 CFD-Predicted R-1234ze(E) Concentrations for Medium-Sized Leak (1.5 g/s), Utility Closet Release Scenario (Open Door)

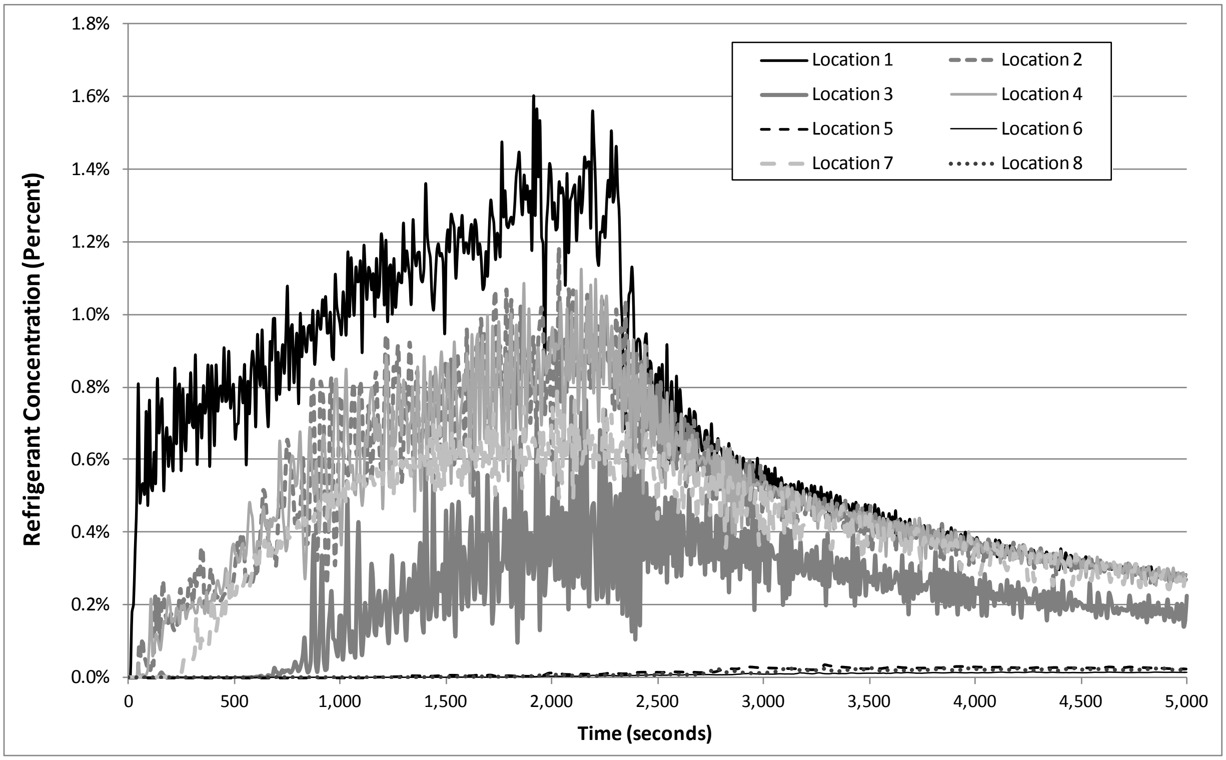


Figure 3.15 CFD-Predicted R-1234ze(E) Concentrations for Medium-Sized Leak (1.5 g/s), Utility Closet Release Scenario (Closed Door)

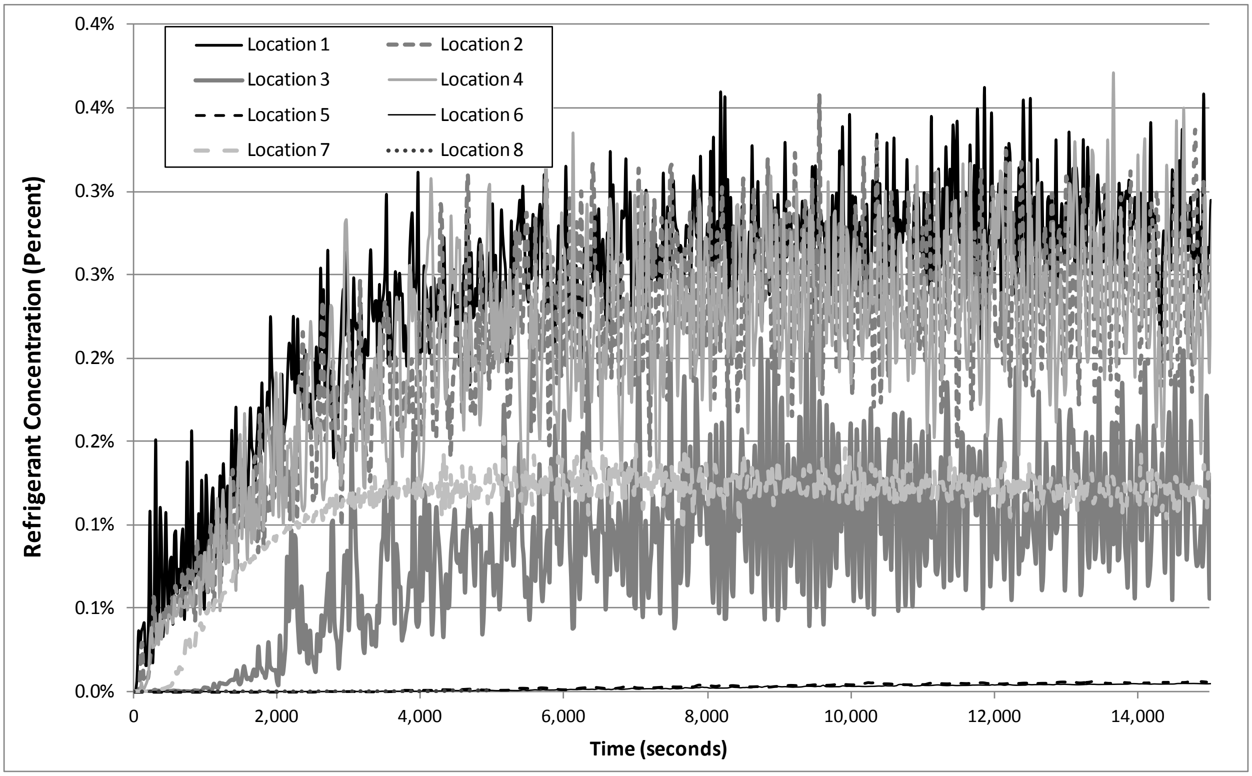


Figure 3.16 CFD-Predicted R-1234ze(E) Concentrations for Small-Sized Leak (0.15 g/s), Utility Closet Release Scenario (Open Door)

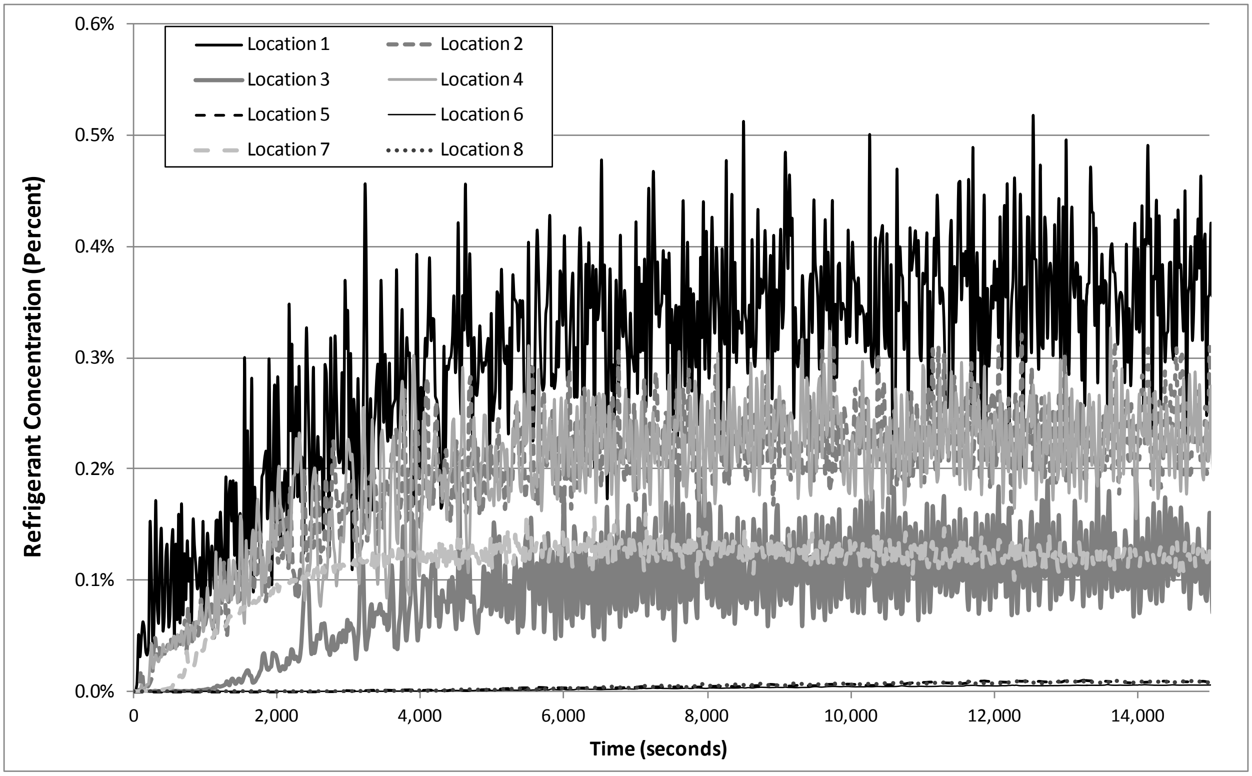


Figure 3.17 CFD-Predicted R-1234ze(E) Concentrations for Small-Sized Leak (0.15 g/s), Utility Closet Release Scenario (Closed Door)

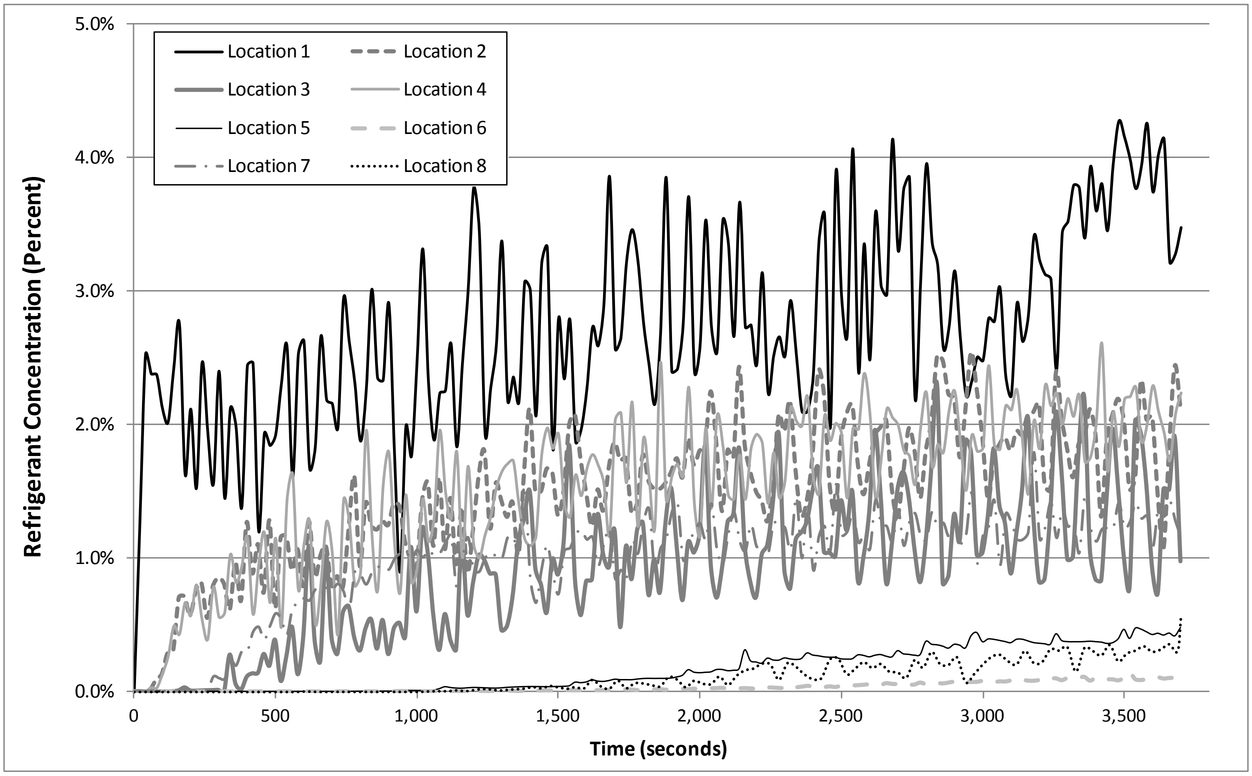
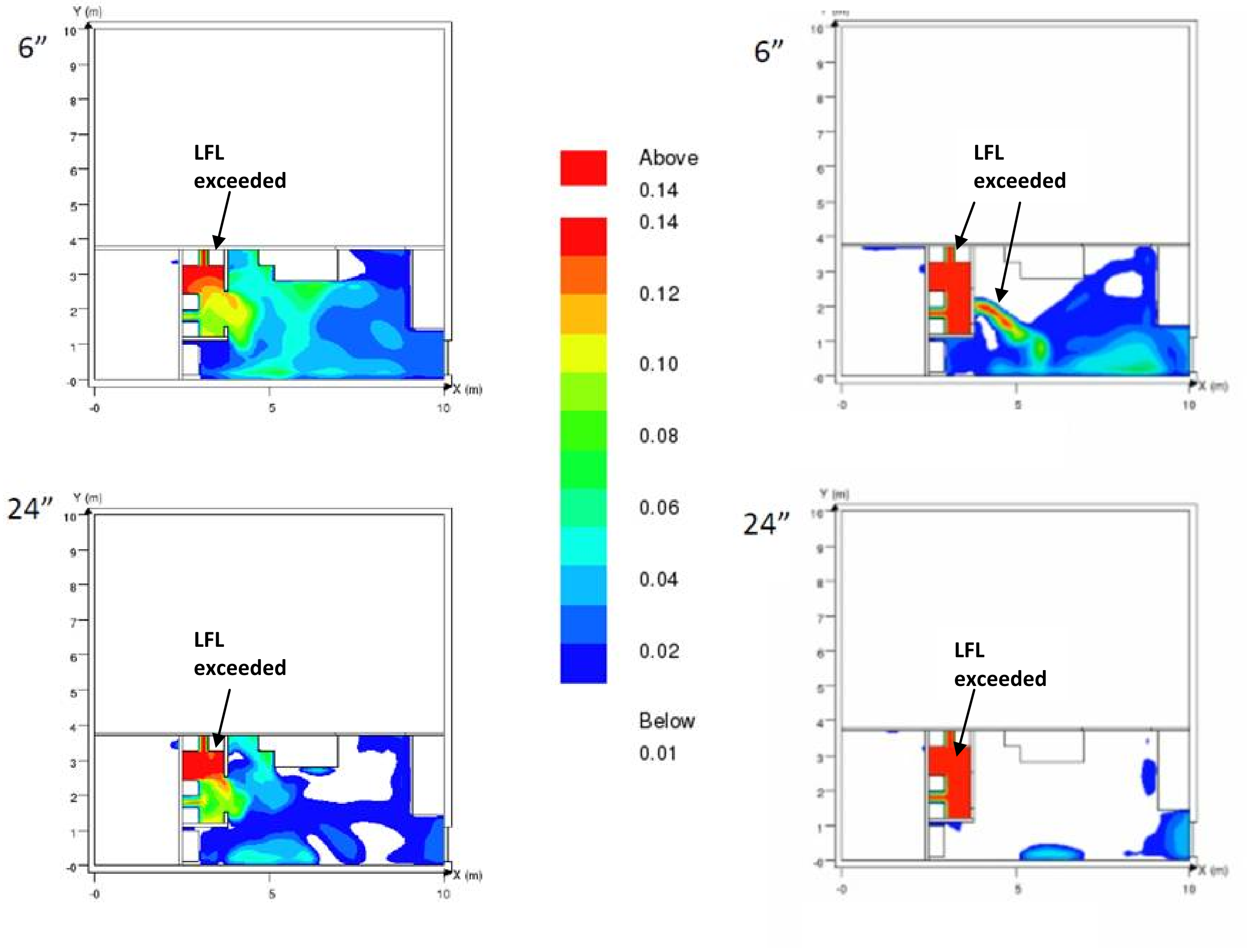


Figure 3.18 CFD-Predicted R-32 Concentrations for Medium-Sized Leak (1.5 g/s), Utility Closet (door closed) Release Scenario (5.45 kg charge)



R-32 Utility Closet Door Open

R-32 Utility Closet Door Closed

Figure 3.19 Screen Capture from Simulation Videos of R-32 Release in Utility Closet Scenario at Maximum Spatial Extent of Region Exceeding the Lower Flammable Limit

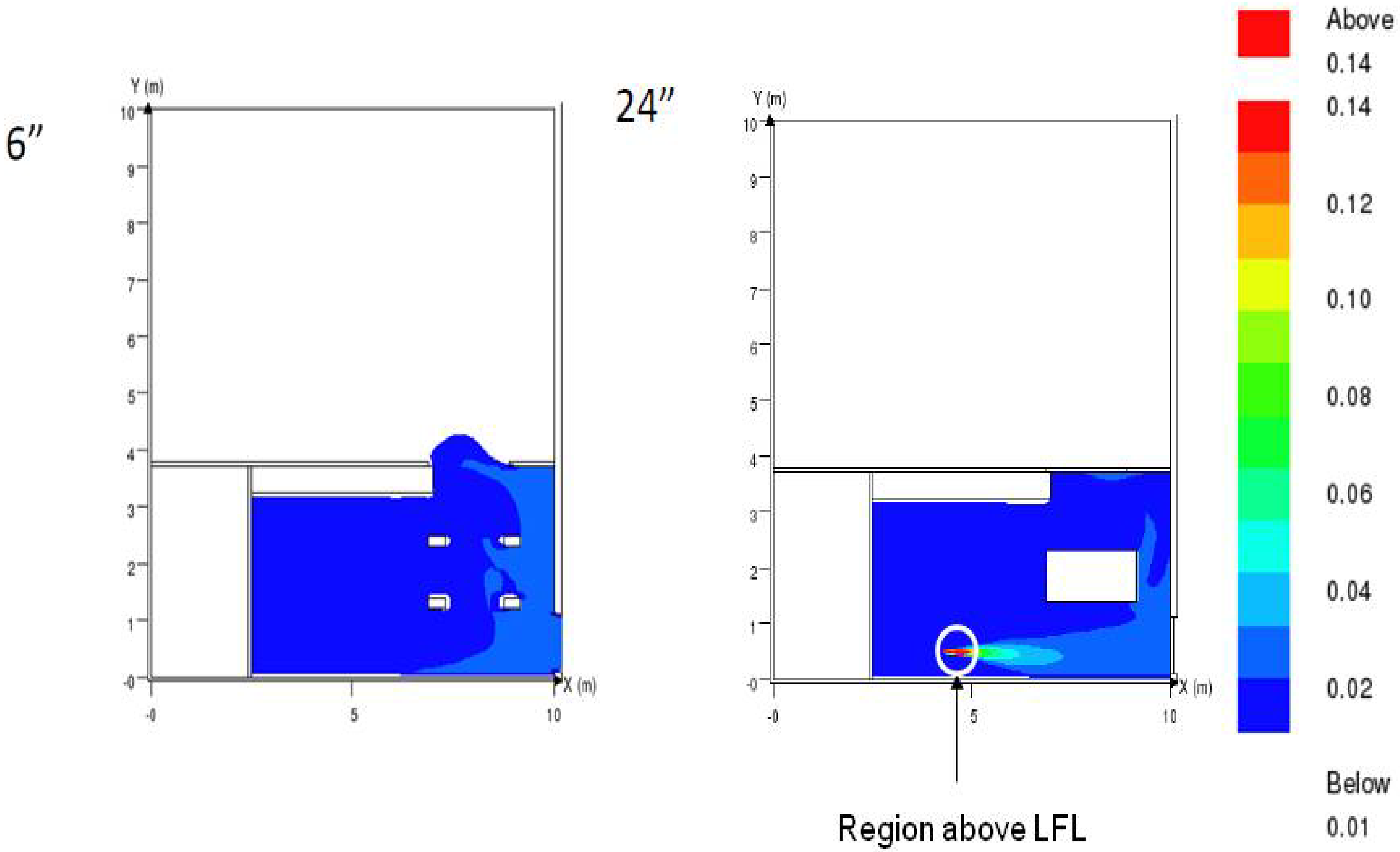


Figure 3.20 Screen Capture from Simulation Videos of R-32 Release in Basement Scenario Indicating Narrow Refrigerant Plume Exceeding the Lower Flammable Limit

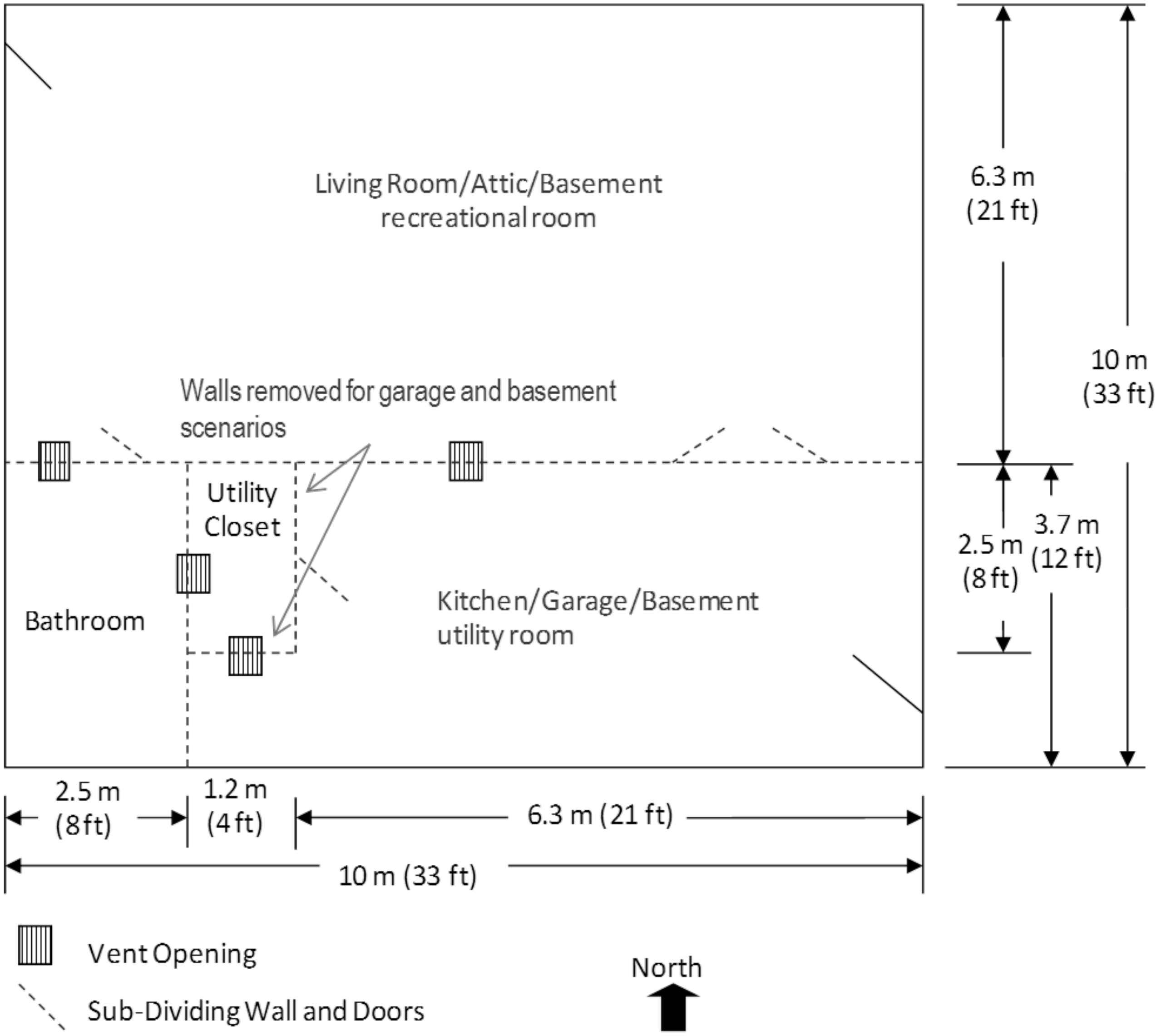


Figure 3.21 Dimensions of Mock-Up Used for Experimental Testing

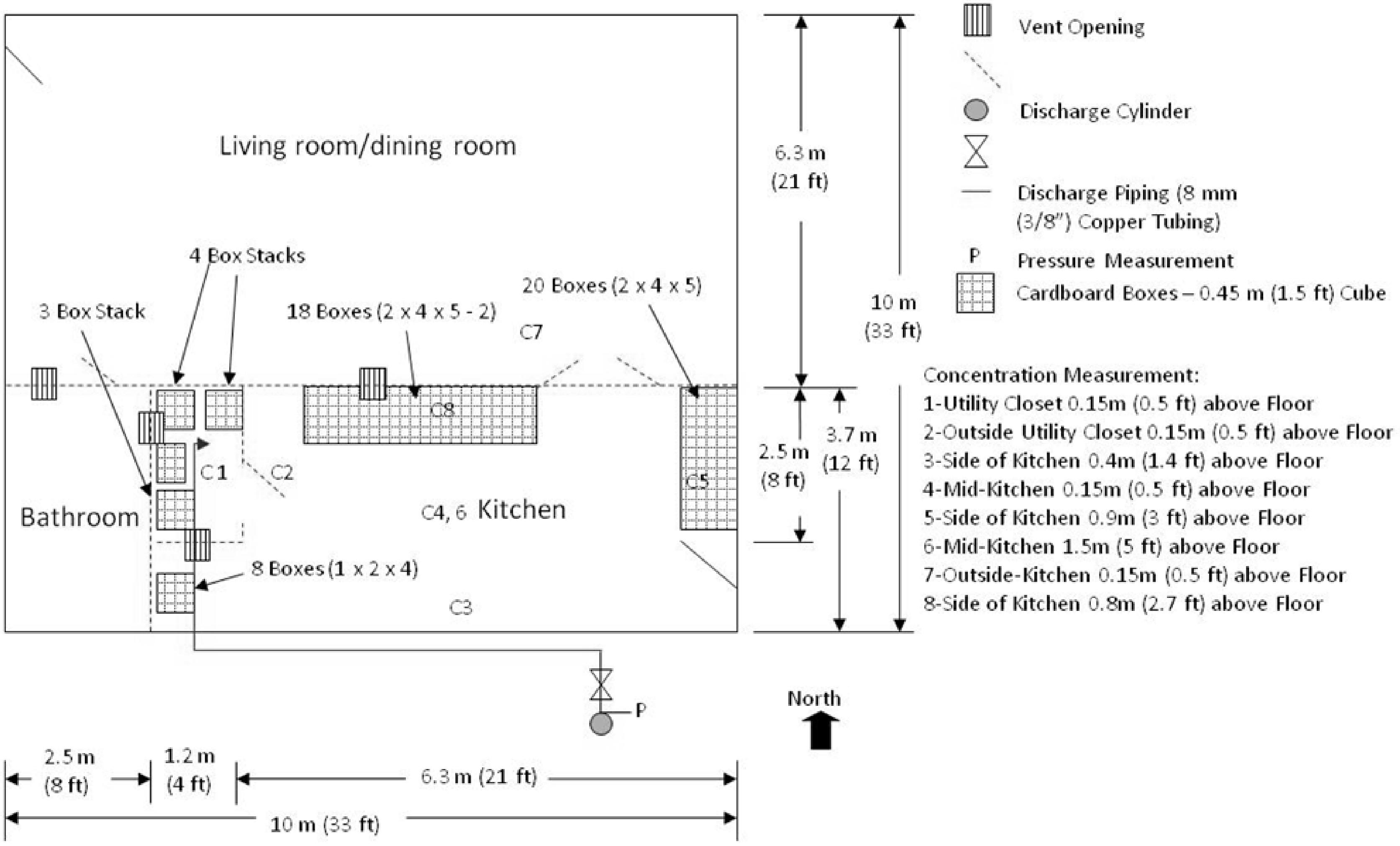


Figure 3.22 Mock-Up of Experimental Testing Configured for Utility Closet Release Scenario Showing Release Point and Simulated Structures in Utility Closet and Kitchen

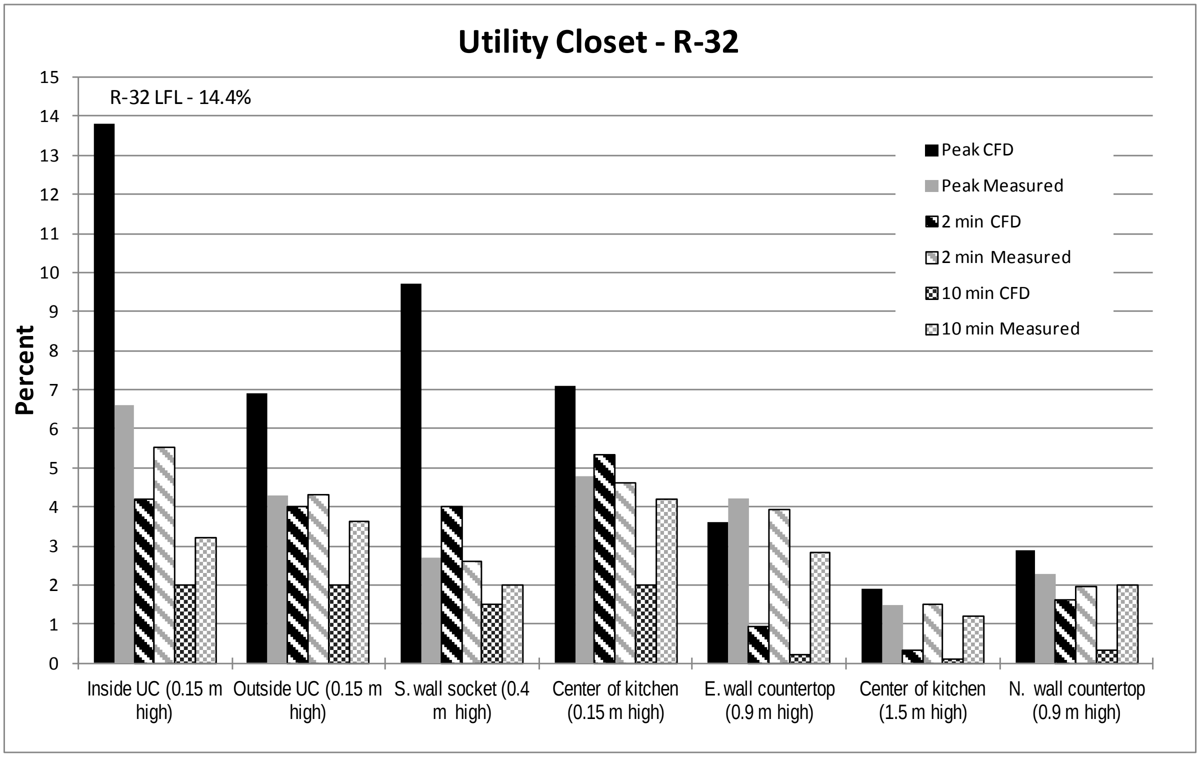


Figure 3.23 Comparison of CFD Modeling and Experimental Testing Results, R-32, Utility Closet Release Scenario (Open Door)

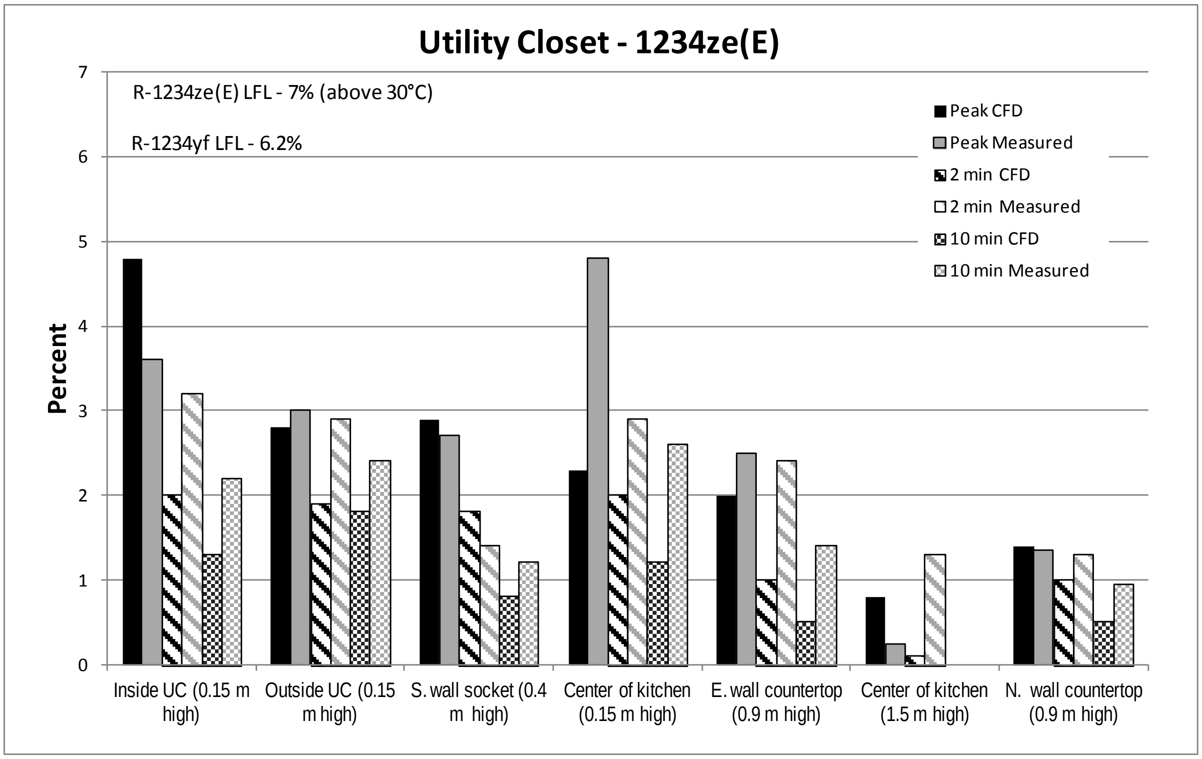


Figure 3.24 Comparison of CFD Modeling and Experimental Testing Results, R-1234ze(E), Utility Closet Release Scenario (Open Door)

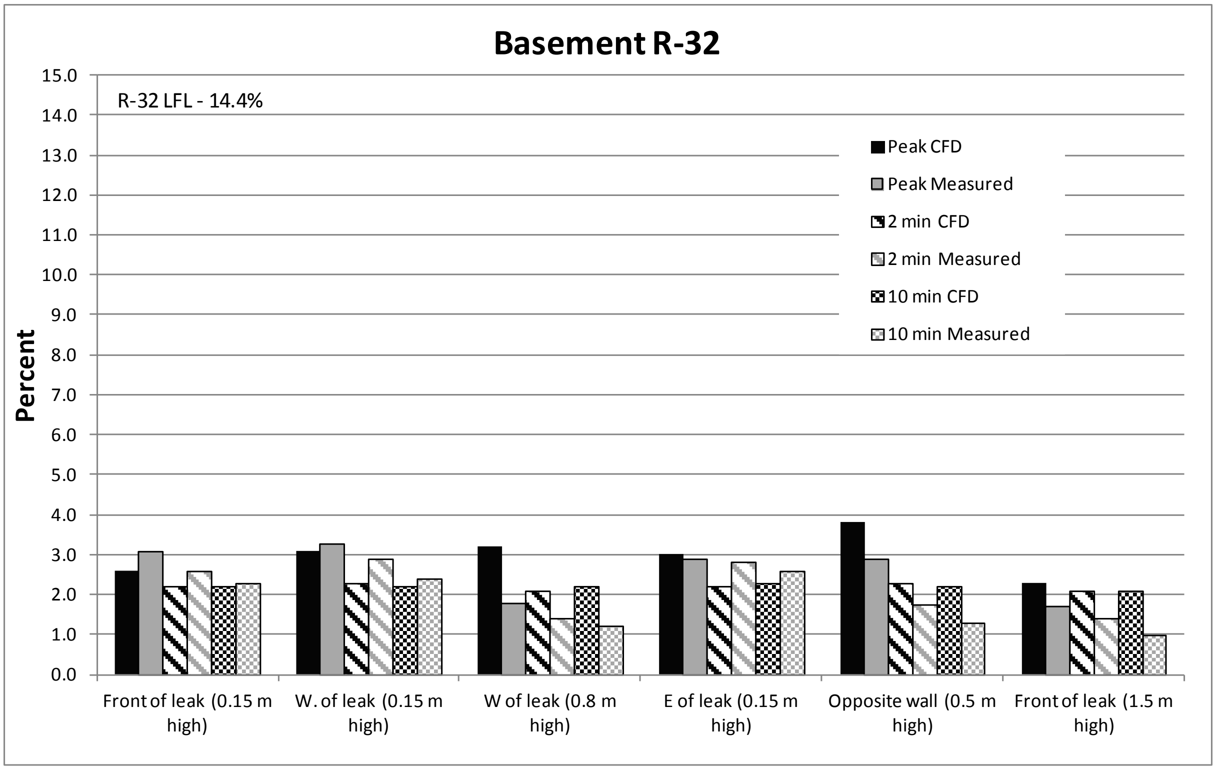


Figure 3.25 Comparison of CFD Modeling and Experimental Testing Results, R-32, Basement Release Scenario

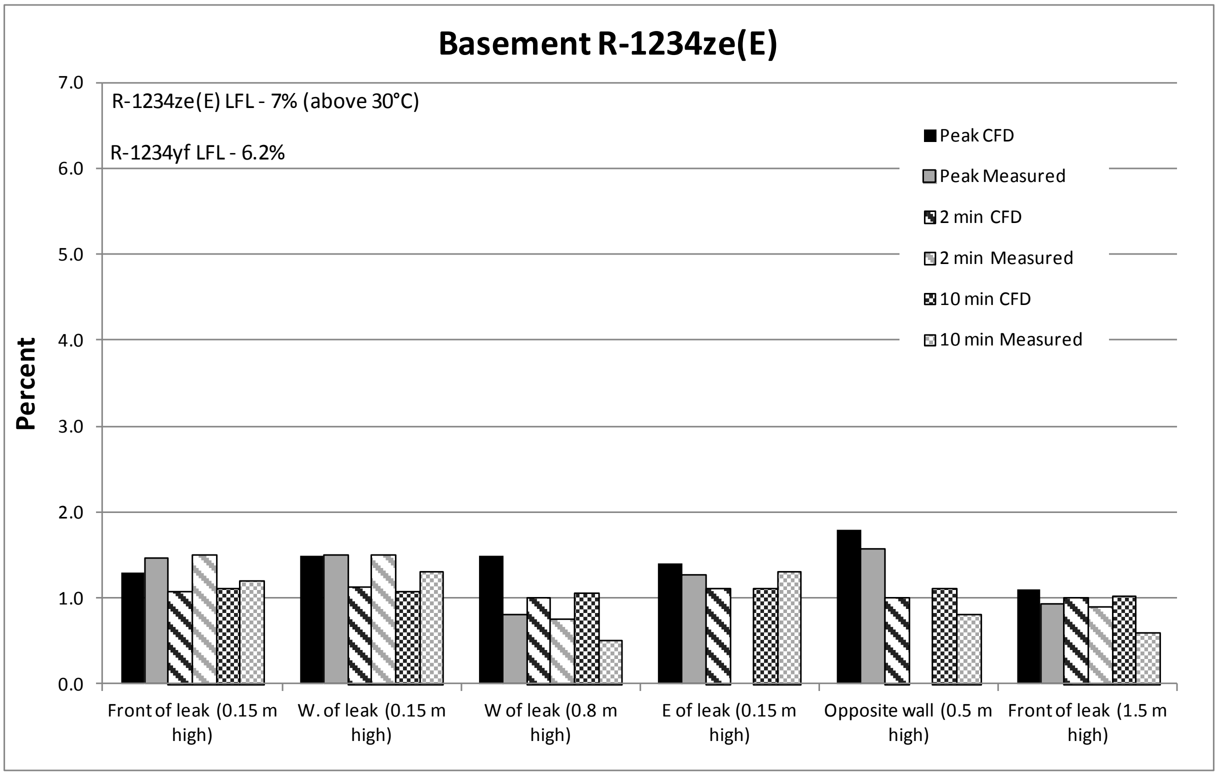


Figure 3.26 Comparison of CFD Modeling and Experimental Testing Results, R-1234ze(E), Basement Release Scenario

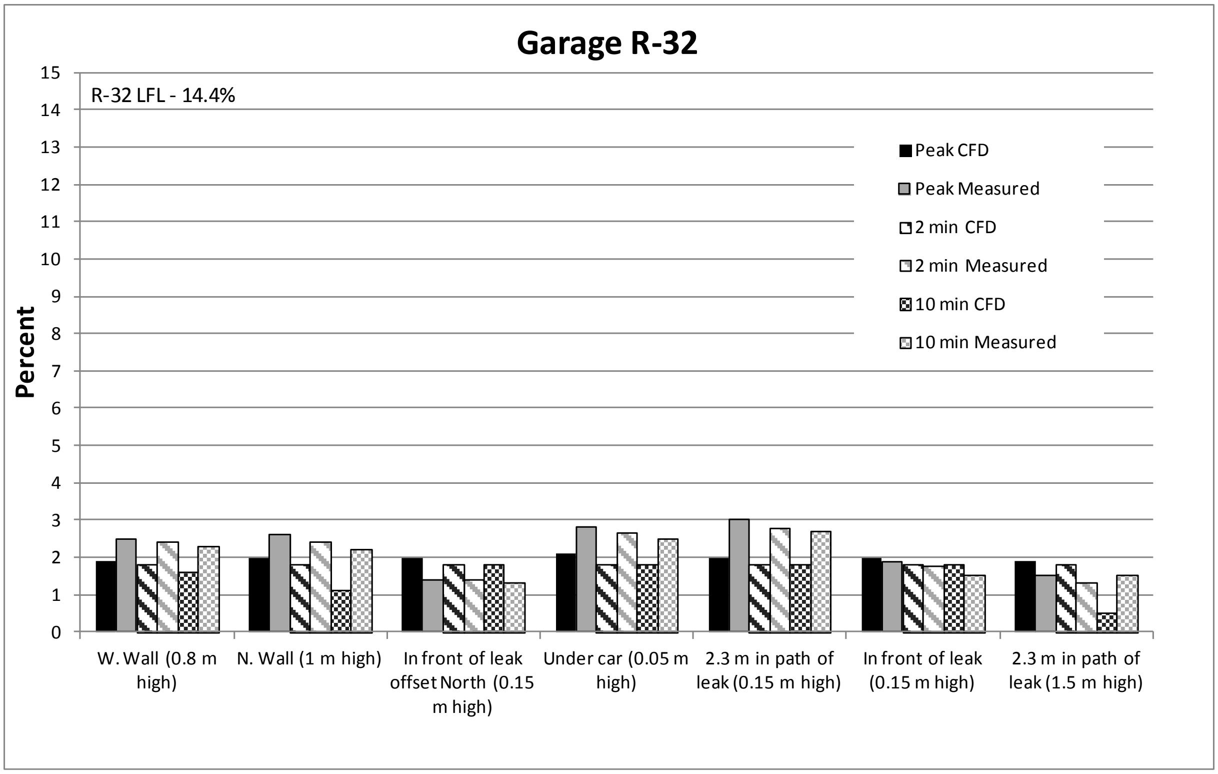


Figure 3.27 Comparison of CFD Modeling and Experimental Testing Results, R-32, Garage Release Scenario

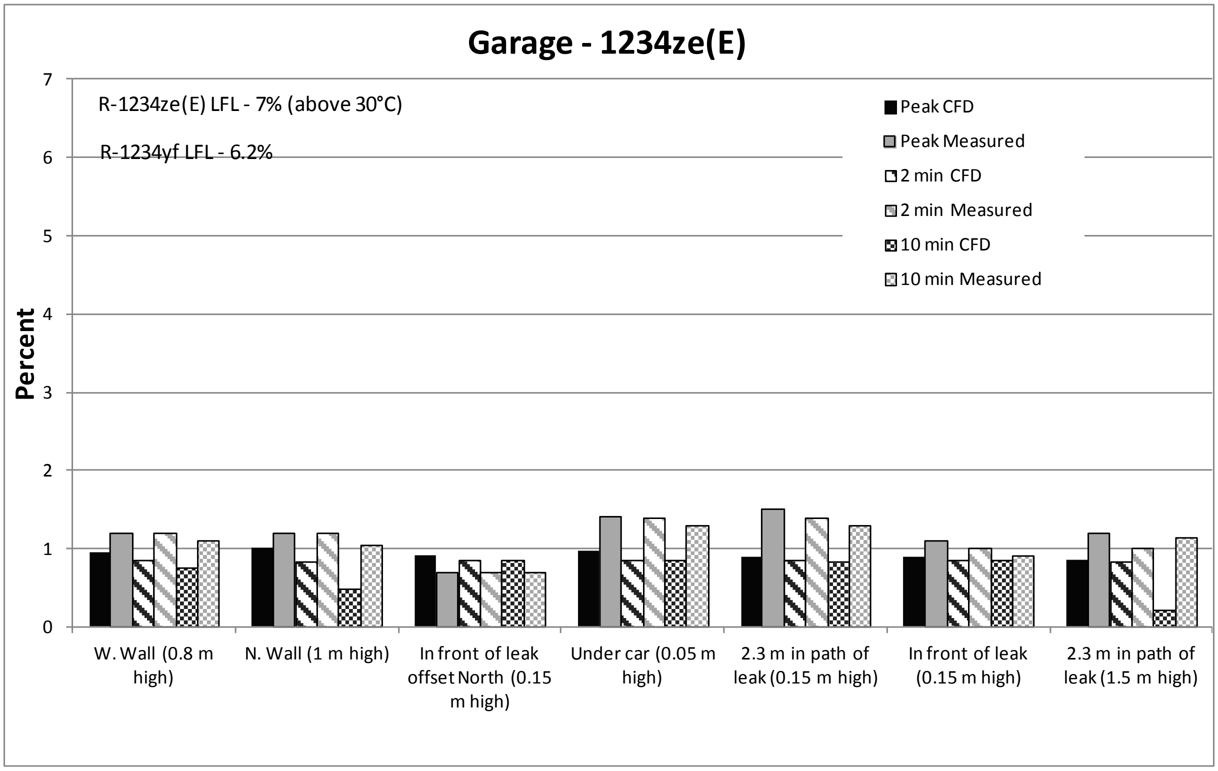


Figure 3.28 Comparison of CFD Modeling and Experimental Testing Results, R-1234ze(E), Garage Release Scenario

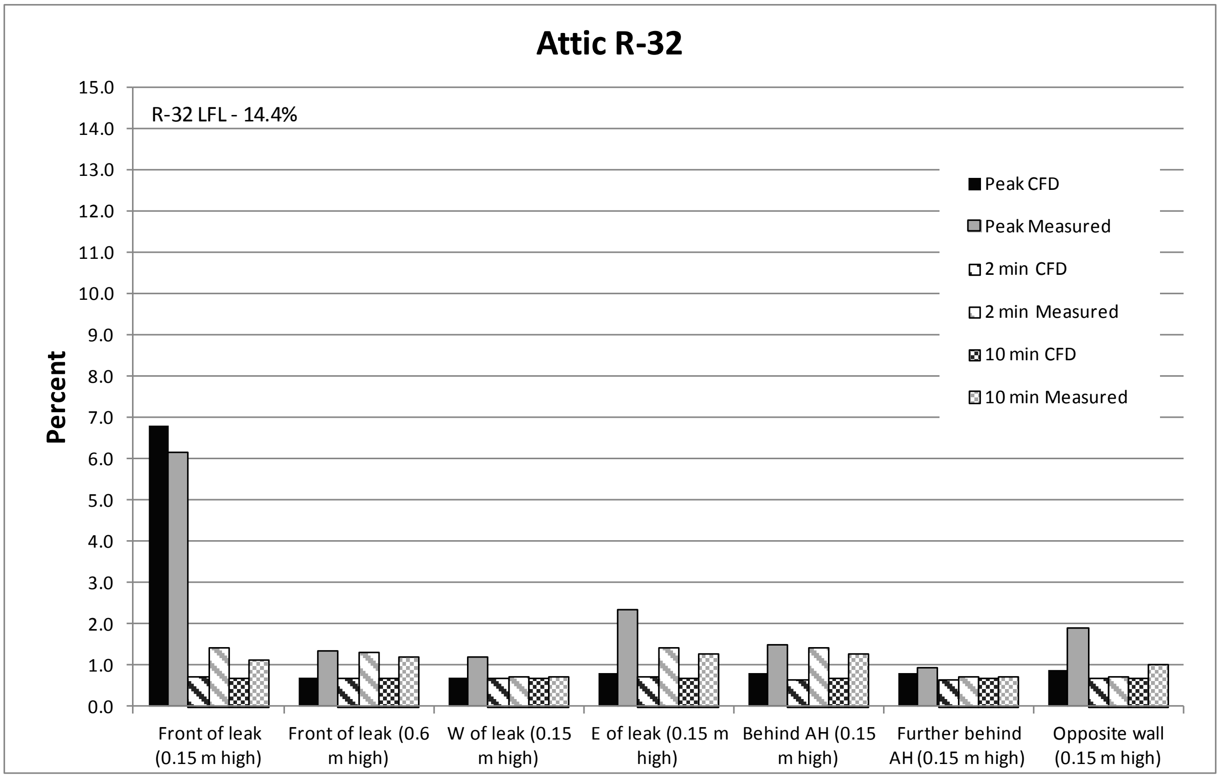


Figure 3.29 Comparison of CFD Modeling and Experimental Testing Results, R-32, Attic Release Scenario

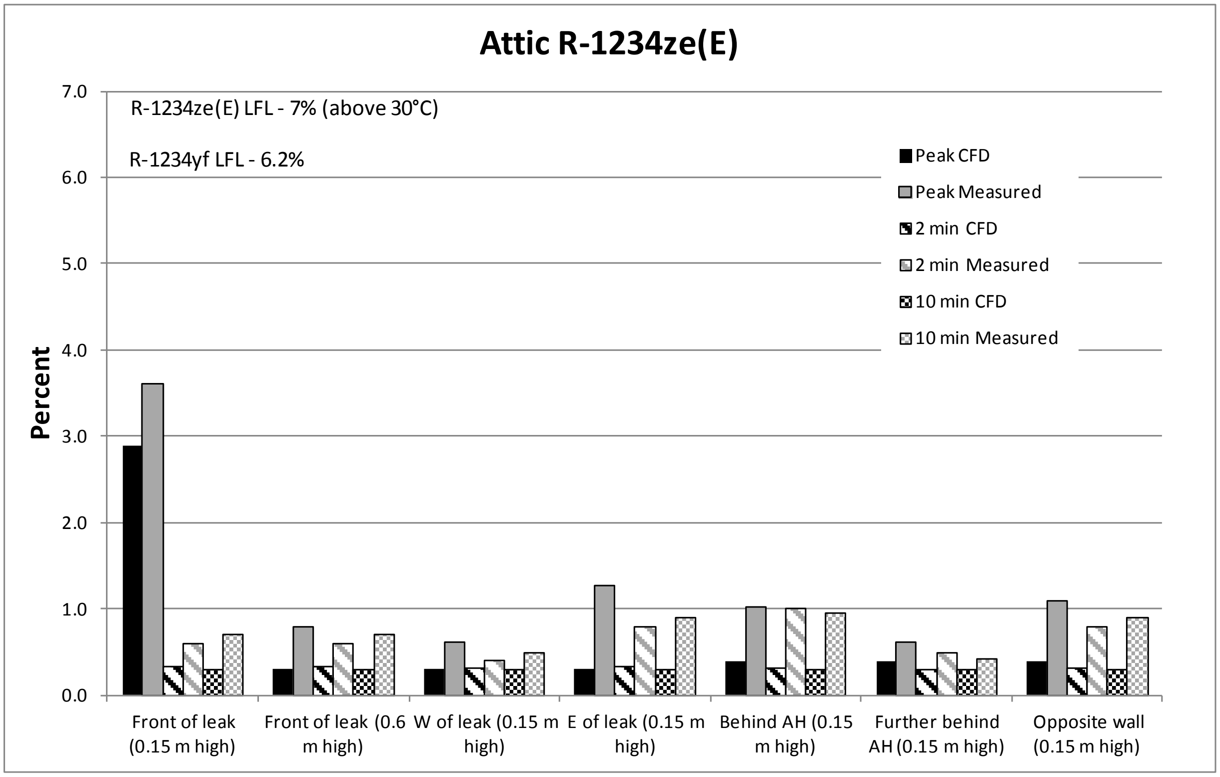


Figure 3.30 Comparison of CFD Modeling and Experimental Testing Results, R-1234ze(E), Attic Release Scenario

4 Fault Tree Analysis (FTA)

4.1 Fault Tree Analysis

To quantify potential refrigerant ignition risks, we used FTA. The goal of FTA is to provide an order of magnitude estimate of the likelihood that outcome in question will occur (US NRC, 1981). It utilizes a "top-down" approach, starting with the undesired effect as the top event of a tree of logic. Fault trees (FTs) consist of various event boxes, which reflect the probability or frequency of key events leading up to a system failure. The event boxes are linked by connectors (gates) which describe how the contributing events may combine to produce the failure. Events may be combined in different ways: in cases where a series of events must all occur to produce an outcome (*e.g.*, ignition source and sufficient oxygen to support combustion), the probabilities or frequencies of the individual contributing events are multiplied *via* an "AND" gate; in cases where only one of a series of events is needed to produce an outcome (*e.g.*, a strong spark, open flame, or a hot surface all possibly leading to refrigerant ignition), the probabilities are added *via* an "OR" gate.[6] More complex combinations are possible (*e.g.*, conditional situations in which a series of contributing events must occur in a specific order to produce a failure), but these were not required in the present analysis. FTs were constructed using the program Windchill Fault Tree (PTC, Needham, MA).

4.2 Fault Tree Development

Appendix C contains FTs developed to assess the potential ignition risks of the refrigerants under study. One set of FTs was developed for each refrigerant. The structures of the trees were identical for each refrigerant except that those for R-1234ze(E) included an additional parameter addressing the lack of flammability of R-1234ze(E) at temperatures below 30°C. The FTs were adapted from those published by Goetzler *et al*. (1998) and were expanded to incorporate additional data on heat pump operation and repair. An important consideration in all of the FTs is the requirement that ignition sources have to be present at the same time and location as the flammable concentration of refrigerant. If the refrigerant does not exceed the LFL throughout the room (as estimated by the CFD modeling), the presence of an ignition source in a part of the room where the LFL is not exceeded creates no risk. The CFD modeling described in Section 3.2 also indicated that even when the LFL is exceeded, this only occurs for a limited time (70 s or less). If the time in which a flammable concentration occurs does not coincide with the time a potential ignition source is present (*e.g.*, an open flame is present), there is also no risk. The rationale for each of the FTs is described below.

The first four FTs (FT1 through FT4) relate to leaks from installed heat pumps in four different locations in the home (*i.e.*, garage, basement, attic, and utility closet). In each FT, major branches consider (1) the probability that a flammable concentration of refrigerant will exist in the room in question, and (2) the probability that a sufficient ignition source is present in the room that can ignite the refrigerant. In terms of whether the refrigerant reaches a flammable concentration, two types of leaks were considered: those occurring in the air handler itself and those occurring in the refrigerant piping on the outside of the air handler. The former leaks are more frequent but are less likely to release refrigerant at a large enough

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[6] In the special case when the inputs to an OR gate are probabilities of events that could occur simultaneously (*e.g.*, worker is sleepy/system is defective) and which can each by themselves cause the failure, the math is A+B-A*B. When the probabilities are mutually exclusive (fan is off/fan is on) the math is A+B.

rate to produce flammable concentrations. This section of the FT also requires that the unit is off or idle; if the unit is operating, the refrigerant will not be able to diffuse into the room surrounding the air handler but will be dispersed through the duct work. Regarding the probability of a sufficient ignition source being present, both electronic and flame sources were considered (aside from the attic where flame sources were considered implausible). Electronic sources could include sparks from an electrostatic air cleaner or from non-HVAC related sparks (*e.g.*, wiring shorts, faulty appliances). Flame sources could include unshielded pilot lights or gas burners. It should be noted, however, that Goetzler *et al*. (1998) found pilot lights only produced very small "burn offs" of refrigerant and only when releases were slow enough to limit air turbulence near the ignition source. Please refer to the Goetzler *et al*. study for additional information on potential ignition sources.

FT5 involves leaks occurring in the outdoor portion of the heat pump. Leaks could occur through the failure of an electrical feed-through plug, the condenser piping, or the condenser itself. Assuming the leak occurs when the fan is not running and there is no wind, a large leak of refrigerant could produce a flammable concentration for a short period of time inside the outdoor unit. Potential ignition sources could involve a fault of an electrical feed-through plug, a spark due to a fault of the fan motor, or a spark due to a fault of the unit's electrical controls.[7] Because each of these sources is located within the outdoor unit, they are likely to be present at the same location as the flammable concentration. Whether these shorts have sufficient energy to ignite the refrigerants and occur at the same time as the flammable concentration is an important consideration in this FT. Finally, for R-1234yf and R-1234ze(E), both of which produce extremely unstable flames, FT5 considers whether outdoor air currents are sufficient to quench any ignited refrigerants.

FT6 involves an air handler leak while the unit is off, releasing refrigerant into the ducts that subsequently diffuses into a downstream room where an ignition source could be present. This tree considers separately leaks for units located in utility closets and units located in other locations. In the former case, the pathway of the return air duct may be substantially shorter than in the latter case, producing a slightly higher probability that refrigerant could exceed the flammable concentration in the return air room (the return air location for a unit in a utility closet is also more likely to be a hallway, which would provide a smaller room volume). FT6 also considers electrical ignition sources (*e.g.*, shorts of electrical equipment) and flame sources (*e.g.*, gas burners, fireplaces, candles).

FT7 involves a leak from piping located inside a wall. Although it is fairly unlikely that a leak would occur inside the wall, it could occur if a homeowner mistakenly drives a nail into the wall where the piping is located. Although highly unlikely, it was considered possible that the leak could accumulate to flammable concentrations in wall voids (*i.e.*, areas without insulation) and that an electrical spark, if occurring at the same time, could cause refrigerant ignition.

FT8 involves an air handler leak while the unit is operating, releasing refrigerant into the ducts that is subsequently blown into a downstream room where an ignition source could be present. It therefore represents a complimentary scenario to FTs 1 to 4, which require that the heat pump unit is off, allowing diffusion out of the unit into the surrounding room (*i.e.*, external to the ducts).

FT9 involves a leak of refrigerant within the air handler that is ignited in the air handler itself by heating elements located in the air handler or duct work. Two conditions were considered: (1) a situation where the unit is operating but the blower is not operating for an extended period (*i.e.*, the blower is malfunctioning), and (2) a situation where the leak occurs when the system is idle and the heating

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[7] Goetzler *et al*. (1998) did not examine any of these sources. Testing with a high voltage spark ignitor was able to ignite R-32 depending on how closely the ignition source was to the refrigerant release point.

elements become operational before the blower turns on. This might occur with systems designed to heat the air present in the unit before blowing it into the rest of the house.

FT-R involves a refrigerant leak during a repair situation. It considers four basic conditions where a refrigerant leak could be ignited: (1) if a leak occurs while a service person is brazing a joint indoors, (2) if a leak occurs while a service person is brazing a joint outdoors, (3) if a service person recharges a system and then uses a propane torch to check for a leak, and (4) if the service person vents or improperly recovers refrigerant from a system, producing a flammable concentration in the air, and then uses a match to light a cigarette.

4.3 Fault Tree Input Probabilities

Once the structure of the FTs was established, a number of sources were used to obtain the probabilities assigned to each FT input event. Values on heat pump installation locations were obtained by AHRI from OEM representatives. A number of values related to heat pump failures (*e.g.*, probability of leaks from air handlers or inlet piping) were adopted from the Goetzler *et al*. (1998) study. The values were discussed among the members of the AHRI project monitoring subcommittee, and it was decided that the values were still applicable although probably conservative. Probabilities concerned with the potential for flammable refrigerant concentrations in various locations were determined based on the results of the CFD modeling. The probability of achieving flammable concentrations in the air handler itself was also informed by measurements conducted as part of the prior Goetzler *et al*. study. Failure probabilities for electronic components were obtained from established sources such as the Nuclear Regulatory Commission *Fault Tree Handbook* (US NRC, 1981) or the Department of Defense Reliability Information Analysis Center (RIAC) electronic parts reliability database (RIAC, 1997). Other values were obtained based on interpretation of published nationwide statistics (*e.g.*, number of homes with natural gas service, number of homes with apparent dual heating systems, *etc*.). A number of inputs were based on the commonly used probability for mistakes due to human error (*i.e*., 10^{-2} to 10^{-3}) (Blackman *et al*., 2008). This was particularly important for the service scenario (*e.g.*, the probability a service person would disregard warnings concerning the flammable refrigerant, the probability mechanical safeguards would be removed and not replaced). Finally, a number of inputs were based on the consensus of industry experts with knowledge regarding heat pump design and operation. Table C.1 in Appendix C describes all of the probabilities used in the FTA along with their associated rationales.

4.4 FTA Results

Table 4.1 shows the results of the FTA. Overall, the FTA indicates that the ignition risks associated with the use of R-32, R-1234yf, and R-1234ze(E) in residential heat pump systems are low. For all three refrigerants, the largest ignition risk is associated with a leak in the outdoor portion of the system (FT5). Risks of this event were on the order of 9×10^{-5} events per unit per year for R-32 and 2×10^{-5} events per unit per year for both R-1234yf and R-1234ze(E). The risks for R-1234ze(E) are identical to those for R-1234yf in this scenario because it was assumed that temperatures inside the outdoor unit would be sufficient for R-1234ze(E) to exhibit flammable limits.

For R-32 and R-1234yf, the second highest risk was associated with a leak of refrigerant from a unit located in a utility closet (FT4: R-32: 7×10^{-8} ignition events per unit per year, R-1234yf: 8×10^{-9} ignition events per unit per year). The risk for R-1234ze(E) in this scenario was lower (8×10^{-11}) due to the absence of flammability at ambient temperatures. Risks for the other unit location scenarios (*i.e.*, the garage, basement, and attic; FT1, FT2 and FT3) were more alike for the three refrigerants because the CFD modeling suggested a similar very low likelihood of obtaining refrigerant concentrations in the flammable range in these three rooms. Risks for R-1234ze(E) were still somewhat lower due to the added requirement for temperatures to be above 30°C for the gas to exhibit flammability.

Risks for the other scenarios considered were all substantially lower and had a negligible impact on overall risk:

- Risks for refrigerant ignition due to leaks into rooms providing the return air (FT6) ranged from 3 x 10^{-14} events per unit per year for R-32 and R-1234yf to 3 x 10^{-18} events per unit per year for R-1234ze(E).
- Risks for refrigerant ignition inside a wall due to a piping leak (FT7) ranged from 3 x 10^{-14} events per unit per year for R-32 to 1 x 10^{-16} events per unit per year for R-1234ze(E).
- Risks for refrigerant ignition due to a leak being blown into a room with an ignition source while the unit is on (FT8) ranged from 9 x 10^{-16} events per unit per year for R-32 to 4 x 10^{-20} events per unit per year for R-1234ze(E).
- Risks of refrigerant ignition within the air handler itself (FT9) ranged from 5 x 10^{-10} events per unit per year for R-32 to 2 x 10^{-10} events per unit per year for R-1234yf and R-1234ze(E).
- Risks of refrigerant ignition during service (FT-R) ranged from 5 x 10^{-12} events per unit per year for R-32 to 6 x 10^{-13} events per unit per year for R-1234ze(E).

4.5 Interpretation of FTA Results

The results of FTA alone are of little value unless they can be placed in proper context. In an ideal world, we would all opt for situations that present no risk whatsoever; unfortunately, all facets of life involve some element of risk. The identification and selection of activities that present an acceptable level of risk based on the knowledge available about the risk involved is an important life skill. With this in mind, the risks of refrigerant ignition obtained in the FTA were compared to risks related to other events that can be calculated from data reported in government or scientific publications. This allows one to consider the significance of individual refrigerant risks in an appropriate context. These comparison risks are shown in Table 4.2. As can be seen in this table, the risks due to refrigerant release and ignition (almost entirely attributable to a leak in the outdoor unit) are far below risks of other hazards that are commonly accepted by the public. For example, the overall risks of refrigerant ignition (9 x 10^{-5} for R-32 and 2 x 10^{-5} for R-1234yf and R-1234ze(E)) are well below the risk of a reportable home fire from any cause (1 x 10^{-3} per home per year). Note that the FTA evaluated refrigerant ignition and did not determine whether the ignition resulted in a fire affecting other structures. Not all ignition events are likely to do so and comparison of ignition risks to fire statistics is therefore conservative. The analysis was also done without including potential mitigation factors that would further reduce the probability of refrigerant ignition. Potential mitigation factors could include redesign of high voltage connections to reduce the probability of shorts or installation of non-removable casing around potential ignition sources that would minimize contact with leaked refrigerant.

4.6 Sensitivity Analysis

As with any risk assessment, the current FTA is based on parameters and assumptions that are, to varying degrees, estimates with an inherent amount of uncertainty. In some instances, these values were specified so as to be conservative (*i.e.*, more likely to overestimate overall risk). However, an assessment conducted with only conservative inputs would be certain to result in an overall risk estimate that would be unrealistic. To gauge the impact of some of these parameter choices, a sensitivity analysis was conducted in which certain inputs to the base FTs (provided in Appendix C) were changed to other plausible values and the resulting frequency of the top event (*i.e.*, refrigerant ignition) was then calculated. The new top event frequency was then compared to the value determined *via* the base FTs. Nine different conditions were evaluated in the sensitivity analysis; the rationale for each modification to the FTs and the resulting change in the risk estimates are described below. Table 4.3 presents the results of the sensitivity analysis.

1. A 10-fold reduction in the probability of air handler and inlet piping leaks (Events 6 and 18). This was meant to account for improvements in system design and stability that have likely occurred since the leak probabilities were estimated by Goetzler *et al*. (1998). With this change, the risks for all indoor leak scenarios (FTs 1 to 4, 6, 8, and 9) decrease 10-fold. However, FT5 (ignition in the outdoor unit) is still the dominant contributor to overall risk.
2. A 5-fold reduction in the probability of a sufficient leak in the air handler producing a flammable concentration in the surrounding room (Events 9, 51, 75, 104). Only large leaks are likely to release enough refrigerant to produce flammable concentrations in a surrounding room, and large leaks in the air handler are extremely rare (relative to large leaks in inlet piping). The base assumption that the probability of a sufficiently large leak in the air handler is fifty percent less likely than a sufficiently large leak in the inlet piping may be overly conservative. With this change, risks for all indoor leak scenarios involving air handler leaks into rooms (FTs 1 to 4) decrease, although the air handler leak still contributes more to the risk based on its higher frequency than inlet piping leaks. However, FT5 (ignition in the outdoor unit) is still the dominant contributor to overall risk.
3. Setting the probability of a sufficient leak in the air handler to achieve a flammable concentration equal to that for an inlet piping leak (Events 9, 51, 75, 104). As noted above, industry expert opinion indicates that leaks in the air handler are much less likely than leaks of the inlet piping, but this extreme scenario was considered because air handler leaks dominate the indoor risks. With this change, the estimated risks for FTs 1 to 4 increase slightly (by a factor of 1.5) and air handler leaks contribute proportionally more to risk (because they occur with higher frequency than inlet piping leaks). However, FT5 (ignition in the outdoor unit) is still the major factor determining overall risk.
4. Increasing the probability of having a spark or flame source in the garage (Events 37, 43) by a factor of 5. This was requested by one OEM to account for the possibility that gas grills or other items could be used inside the garage (with the garage door closed, creating minimal air exchange). With this change, the risk of a refrigerant ignition indoors is still dominated by the utility closet scenario (FTs 1 to 4). FT5 (ignition in the outdoor unit) still dominates the overall risk.
5. Lowering the probability that the box around the fan motor circuitry fails to prevent ignition in the event of a leak in the outdoor unit (Event 143). As the outside unit leak scenario is a critical risk driver, units may be redesigned to provide greater safety in units employing flammable refrigerants (*e.g.*, by being non-removable). This change does not affect the overall risk, because the feed-through plug failure is still the more significant ignition source in the outdoor scenario.
6. Increasing the probability of a leak due to a feed-through fault in the outdoor portion of the unit (Event 119) by a factor of 10. Failure data for the feed-through fault were obtained from a Department of Defense database. A commercial plug may have a different design and a different rate of failure than a product built to Department of Defense specifications. This is a critical input to the FTA because the feed-through plug fault drives the risk for the outdoor

scenario (FT5). With this change, the overall risk increases by a factor of 10 for each refrigerant.

7. Decreasing the probability of a feed-through plug failure by a factor of 5 to account for better design (Event 119). As the outside unit leak scenario is an important risk driver, this ignition source could be redesigned to provide greater safety. The feed-through plug fault drives the risk for the outdoor scenario; even reduced 5-fold this is still the case (*i.e.*, the risk of a non-feed-through plug ignition source remains lower).
8. Increasing the probability that a leak inside the air handler is sufficient to form flammable concentrations in the air handler (Event 179) by a factor of 10. Data supporting the base value are from the Goetzler *et al.* (1998) study, which reported that only a large (40 g/s) R-32 leak would form flammable concentrations in part of the air handler. Steering committee members considered this a very low likelihood event (1 x 10^{-5}) because the vast majority of leaks inside the air handler will be small; however, the specific value is uncertain. Increasing the value 10-fold (*i.e.*, to 1 x 10^{-4}), the risks for FT8 (refrigerant ignition in the room at the end of the duct with the heat pump blower on) and FT9 (refrigerant ignition in the air handler itself) increase 10–fold, but the risks are still below risks associated with the outdoor leak. For R-32 and R-1234yf, risks of the utility closet scenario would also still be higher, while for R-1234ze(E), risks for FT9 would be the highest among the indoor scenarios.
9. Decreasing the probability that R-1234yf and R-1234ze(E) leaks inside the air handler are sufficient to form flammable concentrations in the air handler (Event 179) by a factor of 5. Steering committee members considered sufficiently large leaks of R-1234yf and R-1234ze(E) less likely due to the lower system operating pressures involved with these refrigerants relative to R-32. In the base case, the probabilities for these two refrigerants are reduced by fifty percent relative to R-32, but there was an interest in exploring the impact of a more pronounced effect. With this change, the risks for R-1234yf and R-1234ze(E) in FT8 and FT9 decrease proportionally by 5-fold. This has no effect on overall risk because the risks associated with the unaffected utility closet and outdoor leak scenarios are still higher.

While the modifications listed above produced a change in the estimated risks for different FT scenarios, none of the changes were substantial enough to alter the conclusions of the risk assessment (*i.e.*, none changed the overall risk estimate by more than an order of magnitude and each produced ignition risks that were still far below risks of house fires from other causes). This suggests that the reliance on expert opinion to derive particular FT inputs did not substantially influence the results of the assessment.

Table 4.1 Results of Fault Tree Analysis

Scenario	Fault Tree	Risk of Refrigerant Ignition (events per unit per year)		
		R-32	R-1234ze(E)	R-1234yf
Combined		**9 x 10^{-5}**	**2 x 10^{-5}**	**2 x 10^{-5}**
Leak from unit located in garage	1	1 x 10^{-12}	3 x 10^{-13}	1 x 10^{-12}
Leak from unit located in basement	2	2 x 10^{-12}	7 x 10^{-14}	2 x 10^{-12}
Leak from unit located in attic	3	1 x 10^{-12}	3 x 10^{-13}	1 x 10^{-12}
Leak from unit located in utility closet	4	7 x 10^{-8}	8 x 10^{-11}	8 x 10^{-9}
Leak in outdoor unit	5	9 x 10^{-5}	2 x 10^{-5}	2 x 10^{-5}
Leak in room providing return air	6	3 x 10^{-14}	3 x 10^{-18}	3 x 10^{-14}
Leak inside wall	7	3 x 10^{-14}	1 x 10^{-16}	3 x 10^{-15}
Leak in room due to release into duct (blower on)	8	9 x 10^{-16}	4 x 10^{-20}	4 x 10^{-16}
Leak within air handler	9	5 x 10^{-10}	2 x 10^{-10}	2 x 10^{-10}
Leak during service	R	5 x 10^{-12}	6 x 10^{-13}	2 x 10^{-12}

Notes:

Results shown here are rounded to 1 significant figure, consistent with the order of magnitude nature of FTA. Results in Appendix C show greater precision so that the combination of inputs is more easily recognized.

Table 4.2 Comparison of Fault Tree-Derived Risks to the Risks of Other Relevant Hazards

Relevant Hazard	Risk per Person or Home per Year(1)	Source
Slip/fall injury requiring medical treatment	3 x 10^{-2}	CDC, 2012(2)
House fire significant enough to be reported to government or insurance companies	3 x 10^{-3}	NFPA, 2009
Being injured in a house fire (reported or otherwise) that results from cooking activity	9 x 10^{-4}	NFPA, 2009
Experiencing a fatal accident in the home	1 x 10^{-4}	Wilson and Crouch, 1987
Fatal injury at work (all occupations)	4 x 10^{-5}	NSC, 2004
Bodily injury during use of fireworks	4 x 10^{-5}	US CPSC, 2005(3)
Damage to the home due to fireworks-associated fire	1 x 10^{-5}	Hall, 2011, US Census, 2001(4)
Heat pump-related refrigerant ignition, R-32	**9 x 10^{-5}**	**Current analysis**
Heat pump-related refrigerant ignition, R-1234ze(E)	**2 x 10^{-5}**	**Current analysis**
Heat pump-related refrigerant ignition, R-1234yf	**2 x 10^{-5}**	**Current analysis**

Notes:

[1] Assumes only one heat pump system per home.

[2] The total number of unintentional falls treated in US hospitals in 2009 divided by the US population in 2009 (305 million).

[3] Based on hospital emergency room data. Assumes all individuals have an equal likelihood of using fireworks.

[4] Data for 2000 on the number of home fires related to fireworks use divided by the number of US housing units in 2000.

Table 4.3 Sensitivity Analysis Results in Comparison to Final Fault Tree Analysis Results

Input Modification	Input Value Change	Overall Risk of Refrigerant Ignition with Modification (events per unit per year)			Comment
		R-32	R-1234ze(E)	R-1234yf	
Final Results of FTA (Base Case)		**9×10^{-5}**	**2×10^{-5}**	**2×10^{-5}**	
Reduce probability of air handler and inlet piping leaks (Events 6 and 18)	10-fold decrease	9×10^{-5}	2×10^{-5}	2×10^{-5}	Change only affects FTs 1 to 4, 6, 8, and 9; none of which are risk drivers.
Reduce the probability of a sufficient leak in the air handler to achieve a flammable concentration (Events 9, 51, 75, 104)	5-fold decrease	9×10^{-5}	2×10^{-5}	2×10^{-5}	Change only affects FT1 through FT4 which are not risk drivers.
Change the probability of a sufficient leak in the air handler to achieve a flammable concentration to be equal to that for an inlet piping leak (Events 9, 51, 75, 104)	1.5-fold increase	9×10^{-5}	2×10^{-5}	2×10^{-5}	Change only affects FT1 through FT4 which are not risk drivers.
Increase the probability of having a spark or flame source in the garage (Events 37 and 43)	5-fold increase	9×10^{-5}	2×10^{-5}	2×10^{-5}	Change only affects FT1 which is not a risk driver.
Decrease the probability that the box around the fan motor circuitry fails to prevent ignition (Event 143)	10-fold decrease	9×10^{-5}	2×10^{-5}	2×10^{-5}	Change only affects FT1 through FT4 which are not risk drivers.
Increase the probability of a leak due to a feed-through plug fault in the outdoor portion of the unit (Event 119)	10-fold increase	9×10^{-4}	2×10^{-4}	2×10^{-4}	Change only affects FT5, which is a risk driving scenario.
Decrease the probability of a feed-through plug failure by a factor of 5 to account for better design (Event 119)	5-fold decrease	1.8×10^{-5}	4×10^{-6}	4×10^{-6}	Change only affects FT5, which is a risk driving scenario.
Increase the probability that a leak inside the air handler is sufficient to form flammable concentrations in the air handler (Event 179)	10-fold increase	9×10^{-5}	2×10^{-5}	2×10^{-5}	Change only affects FT8 and FT9 which are not risk drivers.
Decrease the probability that R-1234yf and R-1234ze(E) leaks inside the air handler is sufficient to form flammable concentrations in the air handler (Event 179)	5-fold decrease for R-1234yf and R-1234ze(E)	Not Applicable	2×10^{-5}	2×10^{-5}	Change only affects FT8 and FT9 which are not risk drivers.

5 Data Gaps

This risk assessment was geared to address a specific set of questions concerning the use of ASHRAE/ISO 2L refrigerants in split heat pump systems in residential settings. The scope of the risk assessment was constrained by the original request for proposal in terms of what could reasonably be investigated for the allowed cost and timeframe. The assessment was also limited by the data available concerning heat pump design, installation and repair practices. There are a number of data gaps or areas of uncertainty that could be the focus of additional investigation. These data gaps fall into two categories, those arising because data are limited or unavailable, and those related to questions that were outside the scope of the current assessment. Examples of the first type of data gap include the following:

1. *Limited data on leak frequencies and probabilities for current (or potentially future) system designs*. The probabilities for air handler and inlet piping leaks were obtained by ADL and published in the Goetzler *et al*. (1998) study. Steering committee members reviewed these estimates and determined that they would provide an appropriate, if likely conservative, estimate of leak frequencies in future operating systems. More up-to-date data, *e.g.*, warranty service data, could be useful to verify this assumption. Alternatively, it may be possible to examine system designs from 1998 and compare those to current or even planned future designs to assess whether lower leak probabilities would be warranted.
2. *Limited data on refrigerant dispersion from leaks inside an air handler*. The modeling and experimental measurement conducted as part of this study involved leaks from a point source into a room where the indoor portion of the heat pump unit could be located. The work did not include releases *inside* an actual air handler located inside of the room. This was judged impractical both due to differences in air handler design among manufacturers as well as the difficulty of moving and setting up such a system for the different scenarios. The type of leak used in the modeling and experimental studies was more like an inlet piping leak. A leak inside the air handler would be less likely to result in a flammable concentration of refrigerant in a surrounding room because (1) leaks inside the air handler will be smaller (*i.e.*, lower flow rate) than a leak from the inlet piping, and (2) leaks will have to diffuse outside of the air handler into the surrounding room, a process will which likely attenuate the concentration. For the FTA, it was assumed that leaks inside the air handler would be fifty percent less likely to produce flammable concentrations in the surrounding leak as a leak from the inlet piping. Based on the points just mentioned, this is probably too conservative. To address this data gap, the impact of the air handler structure itself on refrigerant flow into a surrounding room could be examined *via* CFD modeling.

3. *Limited data on ignition studies of these refrigerants with various realistic household sources*. The AHRI project monitoring subcommittee spent considerable time discussing whether different types of residential ignition sources (*e.g.*, candles, gas pilot lights with and without flame arrestors, gas burners, electrical shorts) could ignite these refrigerants. Much of that information was obtained by DuPont and Honeywell in testing for other applications. A limited amount of data was obtained by Goetzler *et al*. (1998) although the number of sources was limited (*i.e.*, high energy arcs and pilot lights). To address this data gap, a manuscript could be prepared which described potential residential ignition sources and summarized the available data on the potential of these sources to ignite the refrigerants in question.

The potential impact of several of these data gaps on the results of the risk assessment was considered *via* sensitivity analysis. That analysis showed that the limited nature of the data concerning these inputs was unlikely to affect the conclusions of the FTA and risk assessment. Acquiring data to address these data gaps would result in a revised risk assessment that would have greater certainty and could potentially indicate lower risks. The overall conclusions would not, however, be expected to change.

The second type of data gap relates to questions or issues that were outside the scope of the current risk assessment. These data gaps include the following:

1. *Questions related to refrigerant degradation products*. All fluorocarbon refrigerants decompose under sufficient temperature conditions to produce hydrogen fluoride (HF) and related compounds. This is true for R-410A as well as for R-32, R-1234yf and R-1234ze(E). HF is corrosive and reactive and exposure to HF, at sufficient concentrations, can produce substantial adverse health effects.[8] Exposure to HF *via* thermal decomposition has been cited as a concern for use of hydrofluoro-olefins as automotive refrigerants (US EPA, 2011). However, the situation with residential heat pump applications is different because individuals trapped by a vehicle collision cannot avoid the HF exposure but an analogous situation is unlikely to occur in a residential setting. Due to its low odor threshold (approximately 3 ppm) and high irritancy, individuals will be strongly motivated to leave areas where HF is present and to minimize their exposure. Thus concerns regarding thermal decomposition for automotive applications may not be relevant for residential settings.
2. *Assessment of the effect of humidity on refrigerant ignition.* We did not include humidity as a factor in the final FTA. Although studies have indicated that the 2L refrigerants exhibit slightly increased flammability (*e.g.*, slightly lower LFLs and higher burning velocities) at higher humidities than are used in standard tests (*e.g.*, Takizawa, 2011), the degree of change is relatively limited (*e.g.*, a few tenths of percent in terms of the LFL). The refrigerant concentration data obtained from the modeling and experimental studies suggest that the small effect of humidity on refrigerant flammability would likely fall within the error bands of the concentration measurement. Because the FTA was used to estimate risks on an order of magnitude scale, humidity effects related to refrigerant ignition would have little impact on the risk assessment results. This decision was supported by the members of the AHRI project monitoring subcommittee.
3. *Assessment of risks of refrigerant blends.* This risk assessment was focused on pure compounds and did not address the risks of refrigerant blends. The exact composition of a potential refrigerant blend would depend on a host of factors (*e.g.*, performance, thermal stability, cost, environmental impacts). While the concentration data gathered here might be expected to be

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[8] For example, the 10-minute Acute Exposure Guideline Level (AEGL) for HF at which effects become disabling or irreversible is 95 ppm.

fairly informative of conditions that might be encountered using different blends (assuming all blend components are not markedly different in terms of vapor density), a blend with different flammability properties would result in different estimated risks. A key objective the current analysis was to determine whether use of 2L refrigerants in heat pumps, *in principle*, was worth further exploration and study. Based on the current findings, blend-specific risk assessments would be appropriate.

4. *Non-residential uses*. The risk assessment was limited to individual residential heat pump systems and excluded systems that might be used at office parks or larger residential units (*e.g.*, apartment buildings). A number of important differences exist between these types of systems that make it inappropriate to extrapolate the current findings to other system types. For example, heat pumps used in office parks may have larger charges, different wiring and different ignition sources (*e.g.*, large computer clusters) that would need to be considered. Now that the basic framework for the risk assessment has been established, it would be relatively easy to identify the different elements that would need to be incorporated to address commercial uses. It is possible that some of the data collected in the current effort could be used as well. For example, the refrigerant concentration data collected for the utility closet scenario could be used to describe a small combined utility room or computer server room.

6 Conclusions

This risk assessment was aimed at evaluating the potential risks of using mildly flammable refrigerants (ASHRAE class 2L) in residential split heat pump systems. Although the use of flammable refrigerants in a residential setting would represent a significant departure from industry practice over the past 60 or more years, addressing concerns regarding the GWP potential of fluoroalkanes such as R-410A may require rethinking previous paradigms. If the risk of ignition associated with Class 2L refrigerants is shown to be incrementally small compared to risks associated with other residential ignition hazards, the environmental benefits these refrigerants can provide (in terms of substantially reduced GWP) may be considered an appropriate basis for substitution.

During normal operation, refrigerants will be contained within the heat pump system and will not pose an ignition risk. It is only under accidental release conditions (*e.g.*, due to equipment fatigue, failure or improper repair) that refrigerant can be released with the possibility of refrigerant ignition. For all three refrigerants, risks in the FTA were driven by the scenario involving refrigerant release in the outdoor unit. That risk, estimated at 9 x 10^{-5} events per unit per year for R-32 and 2 x 10^{-5} events per unit per year for both R-1234yf and R-1234ze(E), is well below the overall risk of house fires from any cause (1 x 10^{-3} per home per year). With respect to the risk for indoor release scenarios, the CFD modeling and FTA indicate that 2L refrigerants pose a negligible indoor refrigerant ignition risk if used in heat pumps located in the basement, garage, or attic. Even in the event of a large leak in these locations (146 to 159 g/s for R-32, 94 to 96 g/s for R-1234yf/ze(E)), the refrigerant never exceeded the LFL. It was only when a large leak occurs in a utility closet that the LFL was exceeded for all three refrigerants under study; smaller leaks did not produce refrigerant concentrations above the LFL.

It also is informative to list major differences between the current risk assessment and the previous study done by Goetzler *et al.* (1998). That assessment (focused on R-32 and R-32/134A blends) reported an overall risk of 3.1 x 10^{-6} fires per unit per year for operational and service failures combined. The Goetzler *et al.* assessment assumed that the ignition of refrigerants will actually result in a fire due to the ignition of surrounding materials; however, the current study only considered the likelihood of refrigerant ignition and did not determine whether the ignition will actually result in a fire due to the ignition of surrounding materials. Another important difference is that the outdoor ignition scenario is the risk driver in the current assessment but a secondary scenario in the Goetzler *et al.* assessment. Goetzler *et al*. developed their scenario around the failure of a "fusible plug" which they assumed might only ignite R-32 in one in one thousand cases. The current analysis was built around the failure of an electrical feed through plug and it was assumed that if this component failed, the energy involved would be sufficient to ignite all three refrigerants. The main risk driver in the Goetzler *et al*. analysis was the service scenario, which accounted for eighty-three percent of the authors' total estimated risk. Much of the service risk derives from the use of propane torches to test for leaks, a situation considered to be extremely unlikely at the current time due to advances in technology and the availability of relatively inexpensive safe leak detection equipment. The service scenario was therefore not a major source of ignition risk in the current analysis. The current assessment and that of Goetzler *et al.* do have in common another high risk scenario, namely the utility closet scenario. For this scenario, the risks for R-32 in each analysis are of the same order of magnitude. The current analysis is believed to be more reliable because modeling (and verification measurement) were conducted for realistic room sizes whereas the earlier Goetzler et al. analysis employed a single 4.6 m^2 (49.5 ft^2) room.

The FTA employed a large number of assumptions related to the probabilities of various events occurring. While a number of the probabilities were based on data obtained from the scientific literature or from reliability databases, some were based on interpretation of limited data or the expert judgment of HVAC industry experts. Although these values were derived from a consensus process and were thus representative of a large knowledge base, some uncertainty in these values remains. The impact of the most uncertain probabilities was assessed *via* a sensitivity analysis. While plausible changes in the input assumptions caused a corresponding change in the estimated refrigerant ignition risks, none of the changes were substantial enough to alter the conclusions of the risk assessment. This suggests that the reliance on limited data or expert opinion to derive particular FT inputs did not substantially influence the results of the assessment.

In summary, this risk assessment evaluated the potential ignition risks associated with the use of R-32, R-1234yf and R-1234ze(E) in residential split heat pump systems. Based on CFD modeling, experimental testing, and FTA, the risk assessment indicates that the risks associated with the use of any of these ASHRAE 2L refrigerants are significantly lower than the risks of common hazard events associated with other causes and also well below risks commonly accepted by the public in general.

Table 6.1 Comparison of the Results of the Current Analysis to Goetzler *et al*. (1998)

Risk of Refrigerant Ignition	Current Analysis Results for R-32		Goetzler *et al.* (1998) Results for R-32(1)	
	Fault Tree	Estimated Risk	Fault Tree	Estimated Risk
Overall		**9×10^{-5}**		**3.1×10^{-6}**
Leak from unit located in garage	1	1×10^{-12}	1(2)	8.9×10^{-8}
Leak from unit located in basement	2	2×10^{-12}		
Leak from unit located in attic	3	1×10^{-12}	2	8.2×10^{-9}
Leak from unit located in utility closet	4	7×10^{-8}	3	9.5×10^{-8}
Leak in outdoor unit (3)	5	9×10^{-5}	8	3.2×10^{-7}
Leak in room providing return air	6	3×10^{-14}	9	9×10^{-10}
Leak inside wall	7	3×10^{-14}	7	"negligible"
Leak in room due to release into duct (blower on)	8	9×10^{-16}	5	0
Leak within air handler	9	5×10^{-10}	4	2.2×10^{-10}
Leak during service	R	5×10^{-12}	6	2.6×10^{-6}

Notes:

[1] The study examined R-32 and R-32/R-134a blends but used a single set of fault trees. This study also reported the top event as "risk of fire" although in reality it also assessed refrigerant ignition.

[2] The garage and basement locations were combined in the Goetzler *et al.* (1998) study.

[3] In the Goetzler *et al*. study, the risk for the outdoor scenario was dominated by a release due to failure of a fusible plug. OEM representatives determined that this type of plug is not used in current system designs. The outdoor scenario in the current analysis was dominated by a release from a failure of an electrical feed through plug.

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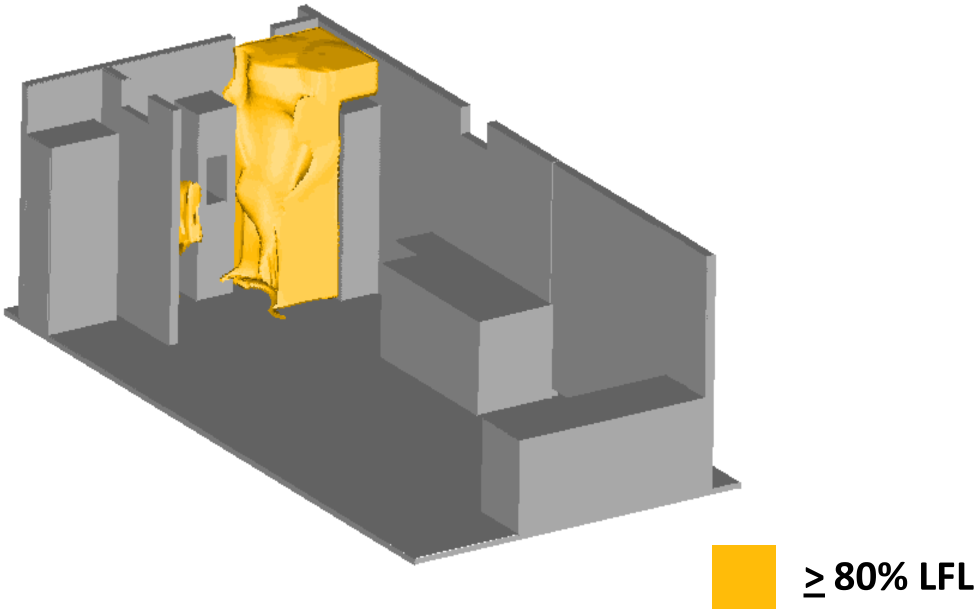
Appendix A

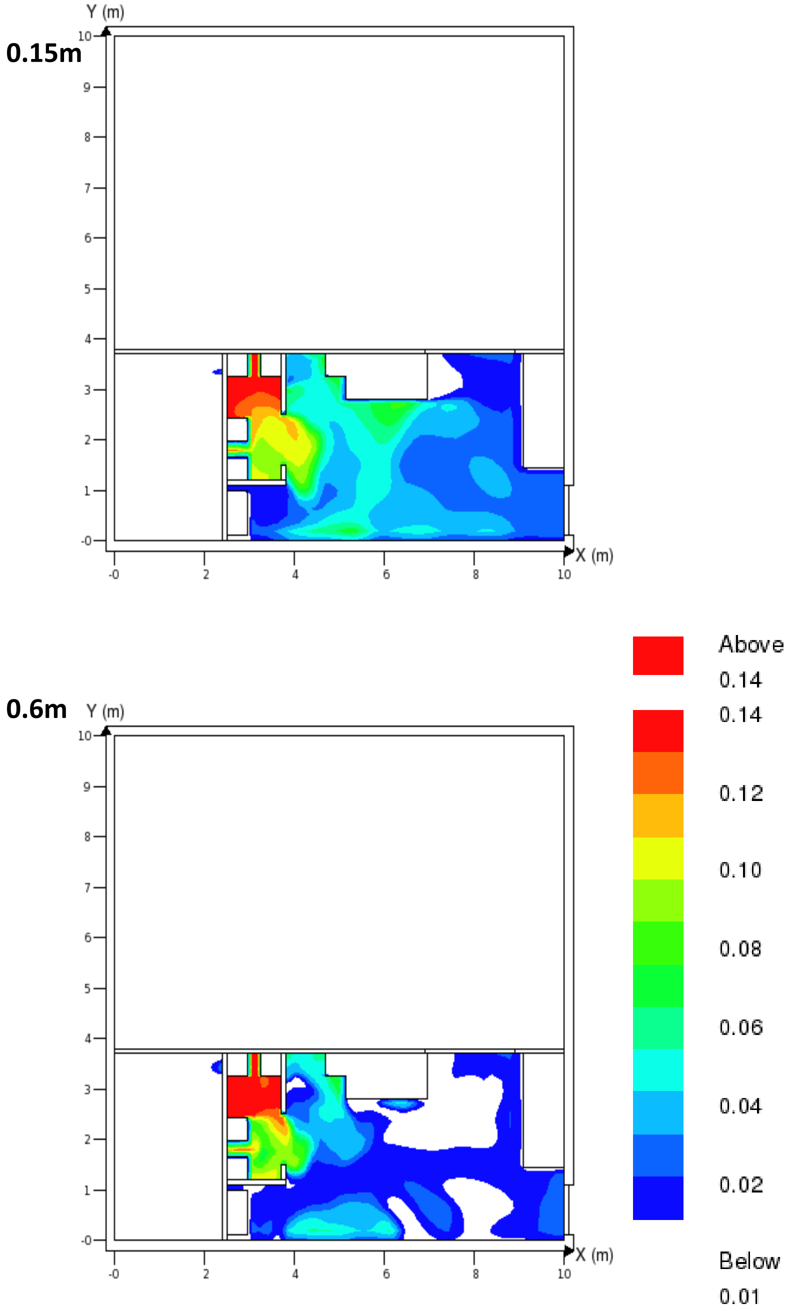
GexCon Modeling Detailed Results

Plots of Refrigerant Concentration

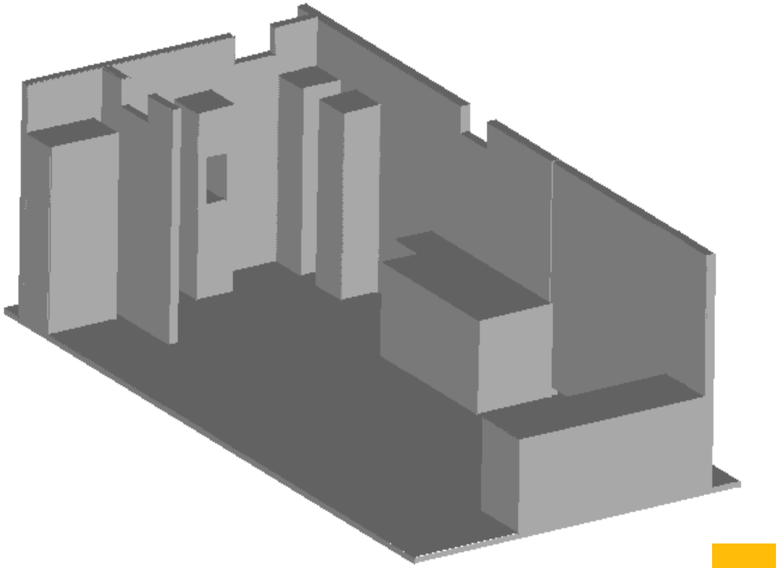
Two types of plots were constructed to show refrigerant dispersion at particular points in time. Three dimensional (3-D) volume plots were developed to provide an image of where the refrigerant is located within the house (note that for the utility closet scenario, the wall between the utility closet and kitchen wall is not shown to allow the viewer to see inside the closet). Showing different concentrations in the same 3-D plot is not possible because areas of higher concentration lie inside areas of lower concentration. Therefore only areas where the refrigerant concentration was 80% of the LFL and above are shown. To provide a better sense of how concentrations varied across the space, two dimensional (2-D) area plots were also created which indicate refrigerant concentration at specific heights. Heights of 0.15 and 0.6 m (6 and 24") were selected as being likely locations of potential ignition sources. In these plots the full range of refrigerant concentrations from <0.1% up to the LFL is indicated.

In the legend for each figure, the time elapsed is how far along the simulation has progressed at the time the screen capture of the release was taken. The leak duration will be less than the total simulation time as each simulation includes the decay phase after the leak when refrigerant settles and diffuses through the entire structure. The following figures generally include screen captures when the refrigerant concentration is near its maximum (generally towards the end of the leak) and at the end of the simulation (showing final concentrations).

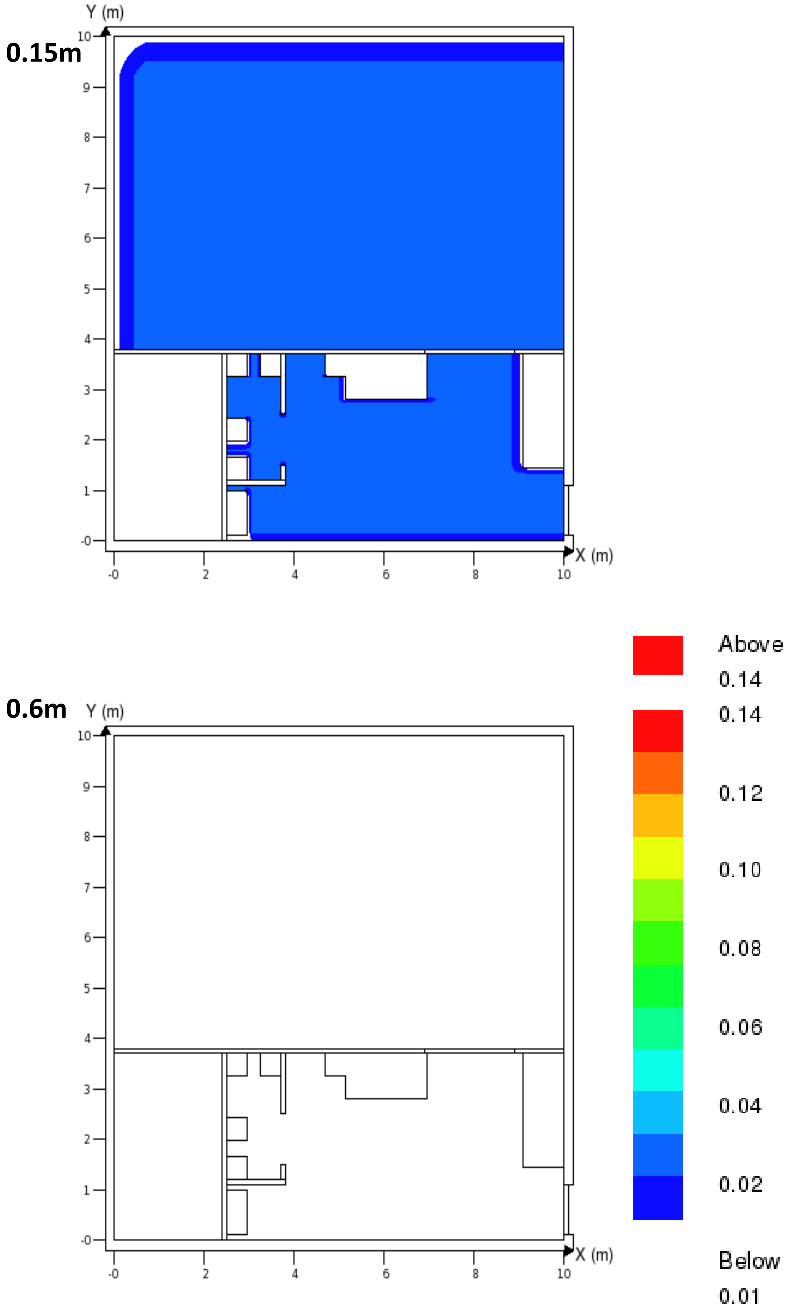




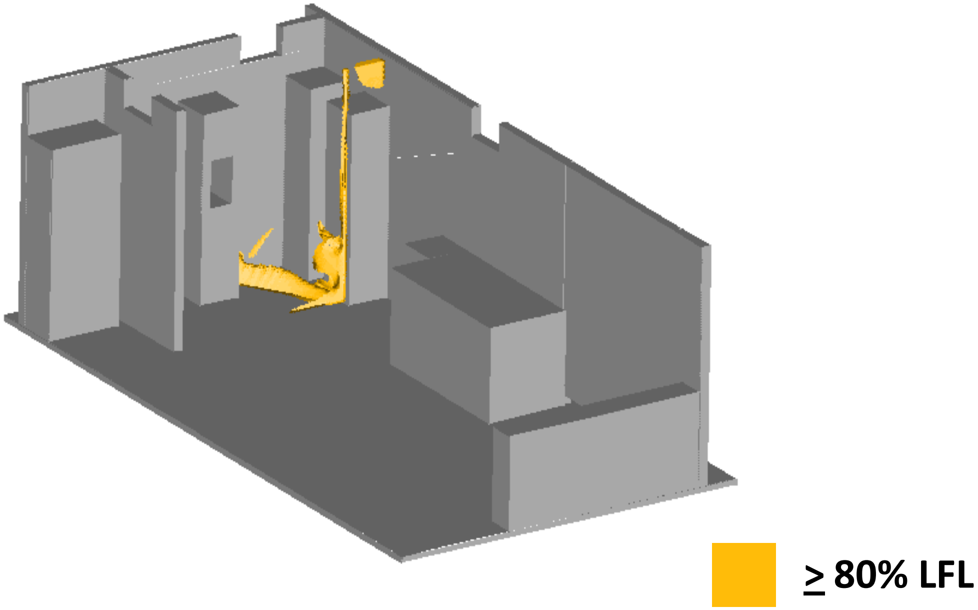
1st floor release : Door open
Case # : 910101
Species : R-32
3D Volume plot of 80% LFL
2D Contours between 1% and 14%
Time elapsed : 20 s
Leak Rate: 0.17 kg/s
Leak Duration : 18 s

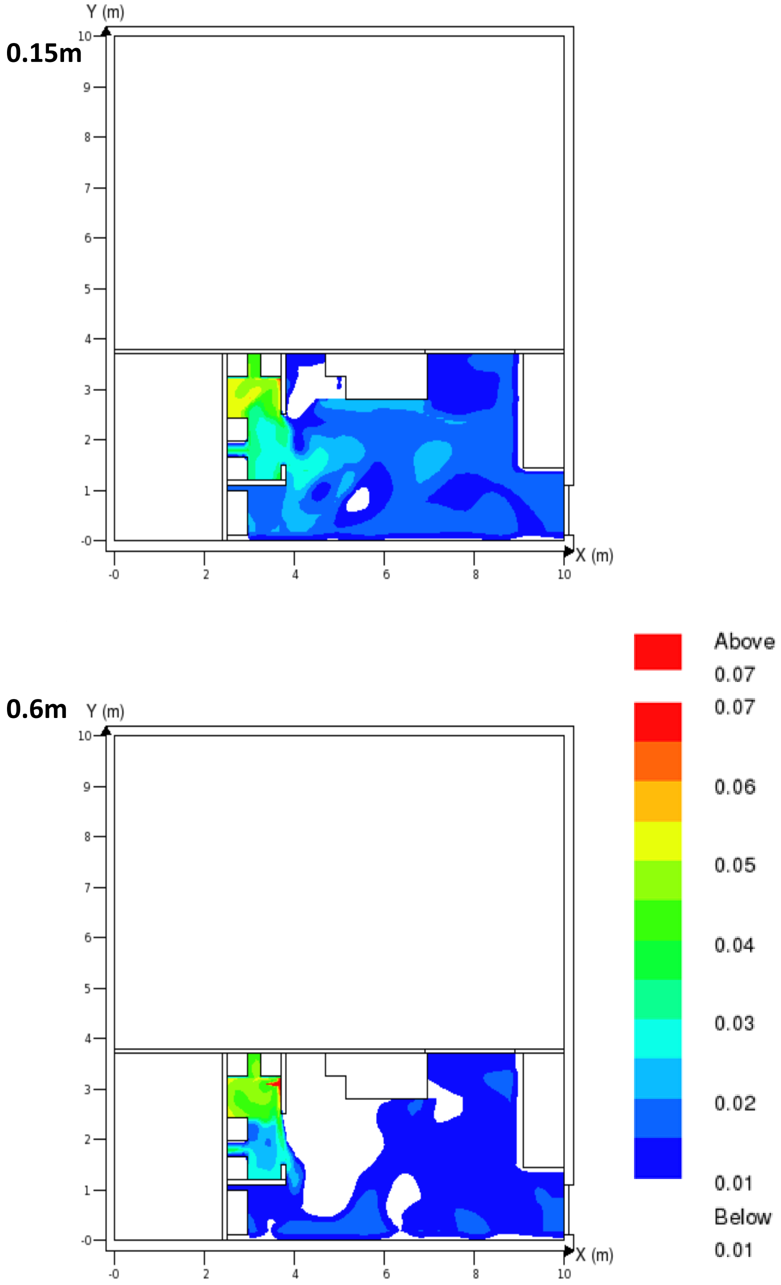


🟧 **≥ 80% LFL**

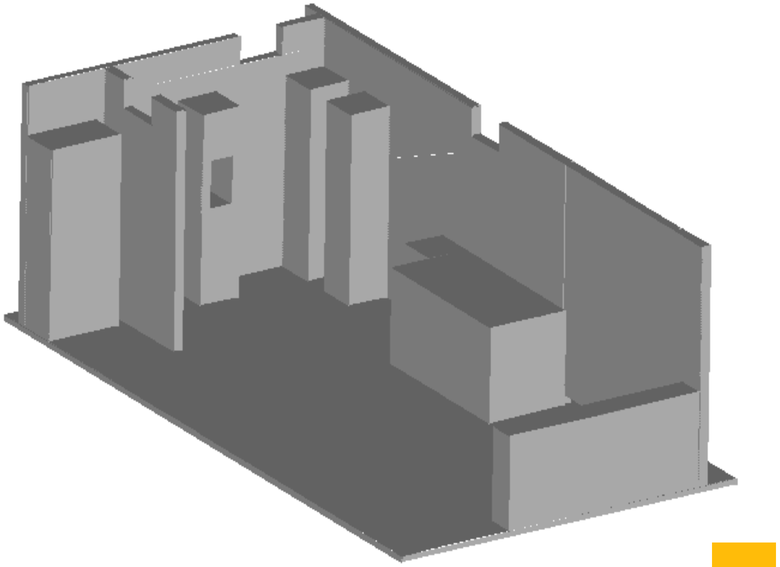


1st floor release : Door open
Case # : 910101
Species : R-32
3D Volume plot of 80% LFL
2D Contours between 1% and 14%
Time elapsed : 1800 s
Leak Rate: 0.17 kg/s
Leak Duration : 18 s





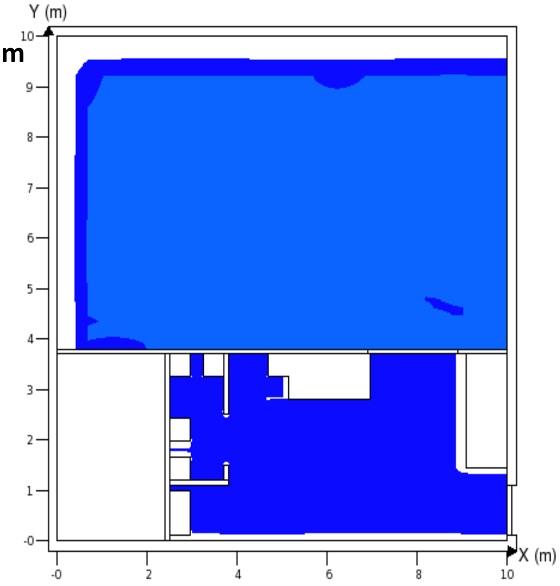
1st floor release : Door open
Case # : 910102
Species : R-1234ze(E)
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed: 35 s
Leak Rate: 0.078 kg/s
Leak Duration: 39 s



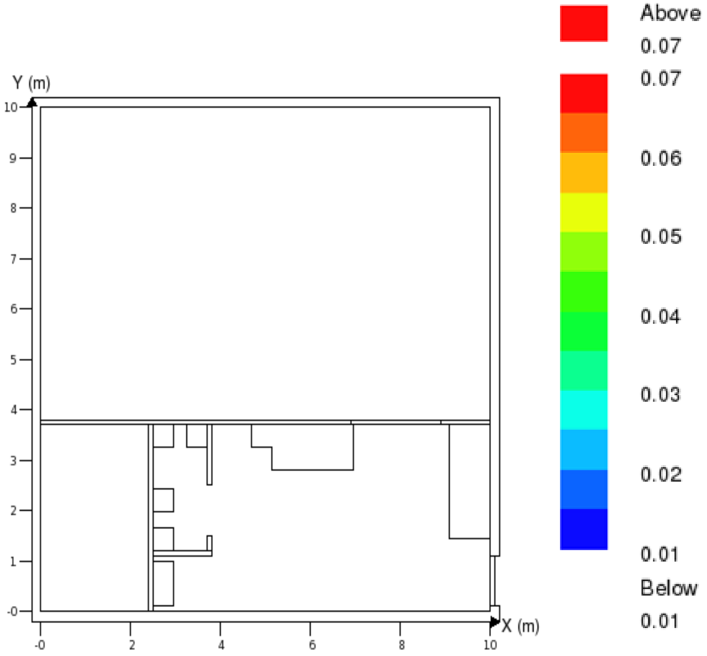
🟧 **≥ 80% LFL**

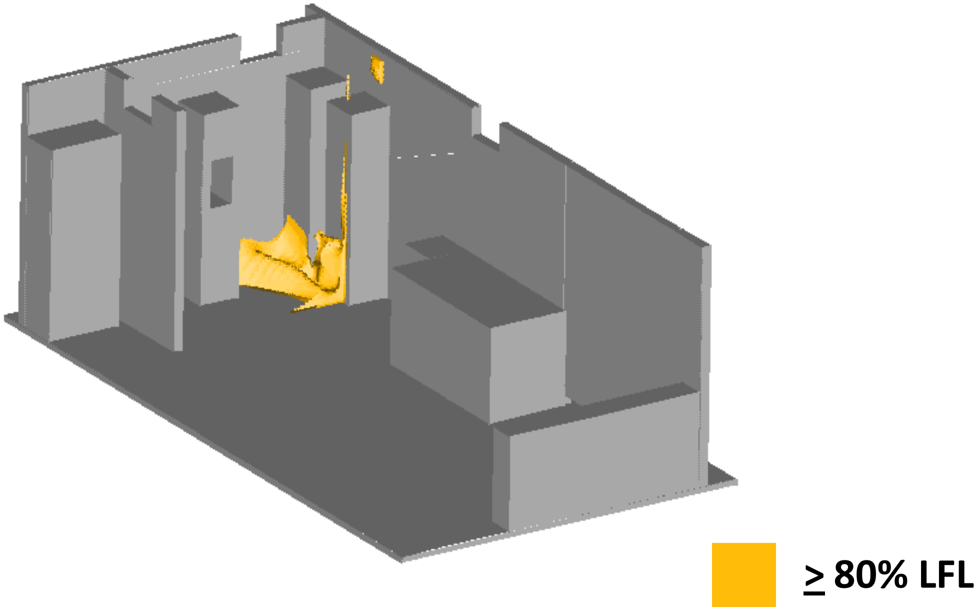
1st floor release : Door open
Case # : 910102
Species : R-1234ze(E)
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed: 660 s
Leak Rate: 0.078 kg/s
Leak Duration: 39 s

0.15m

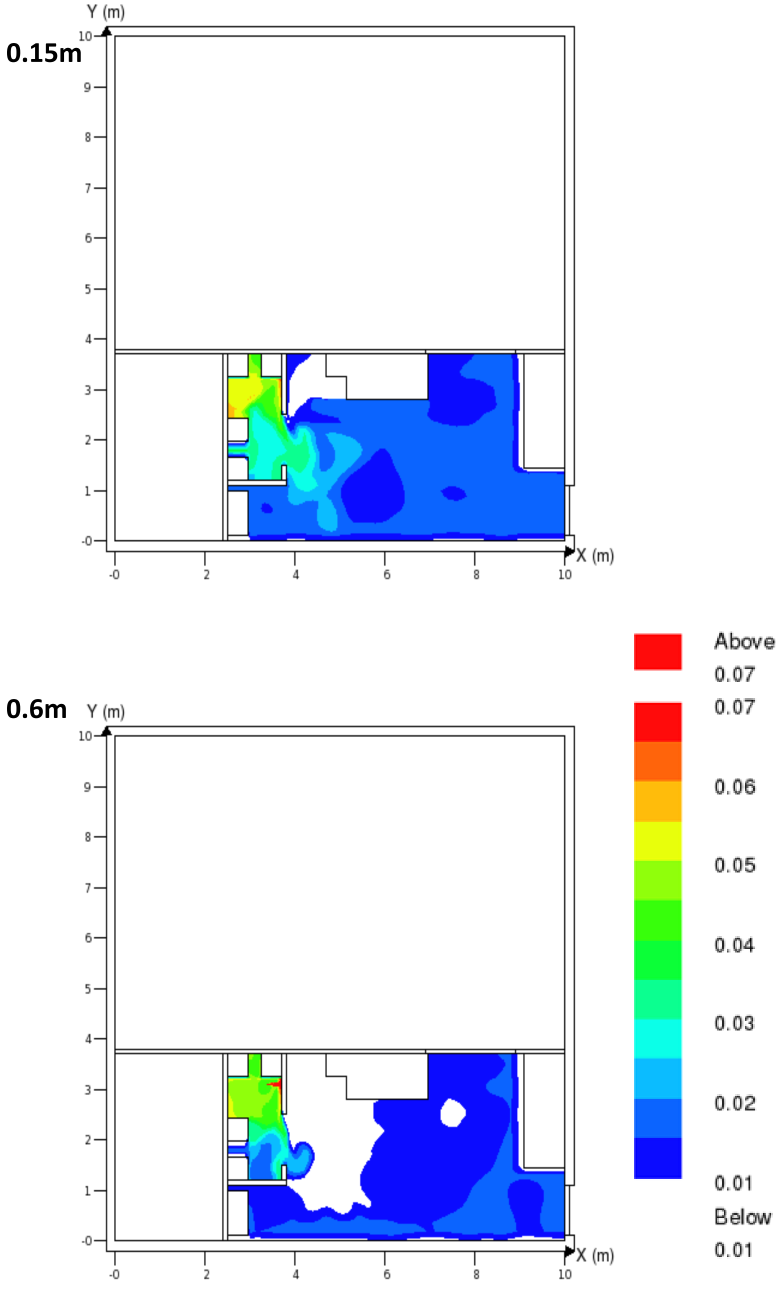


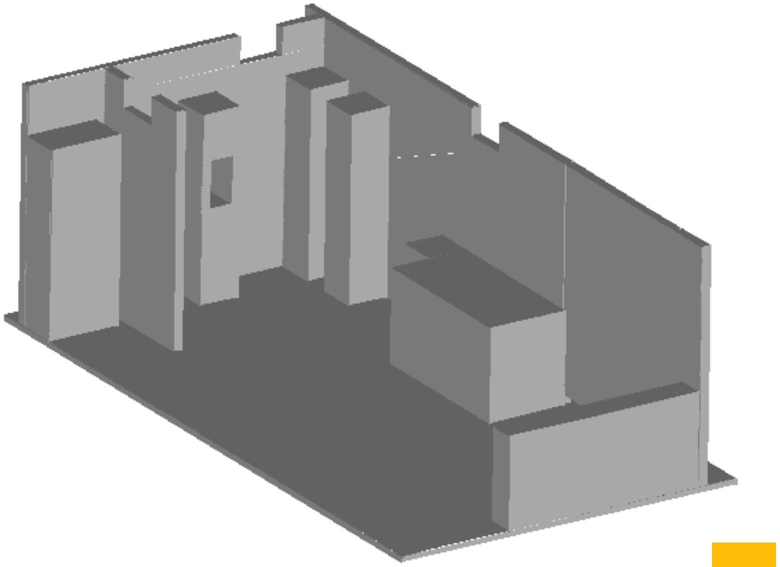
0.6m



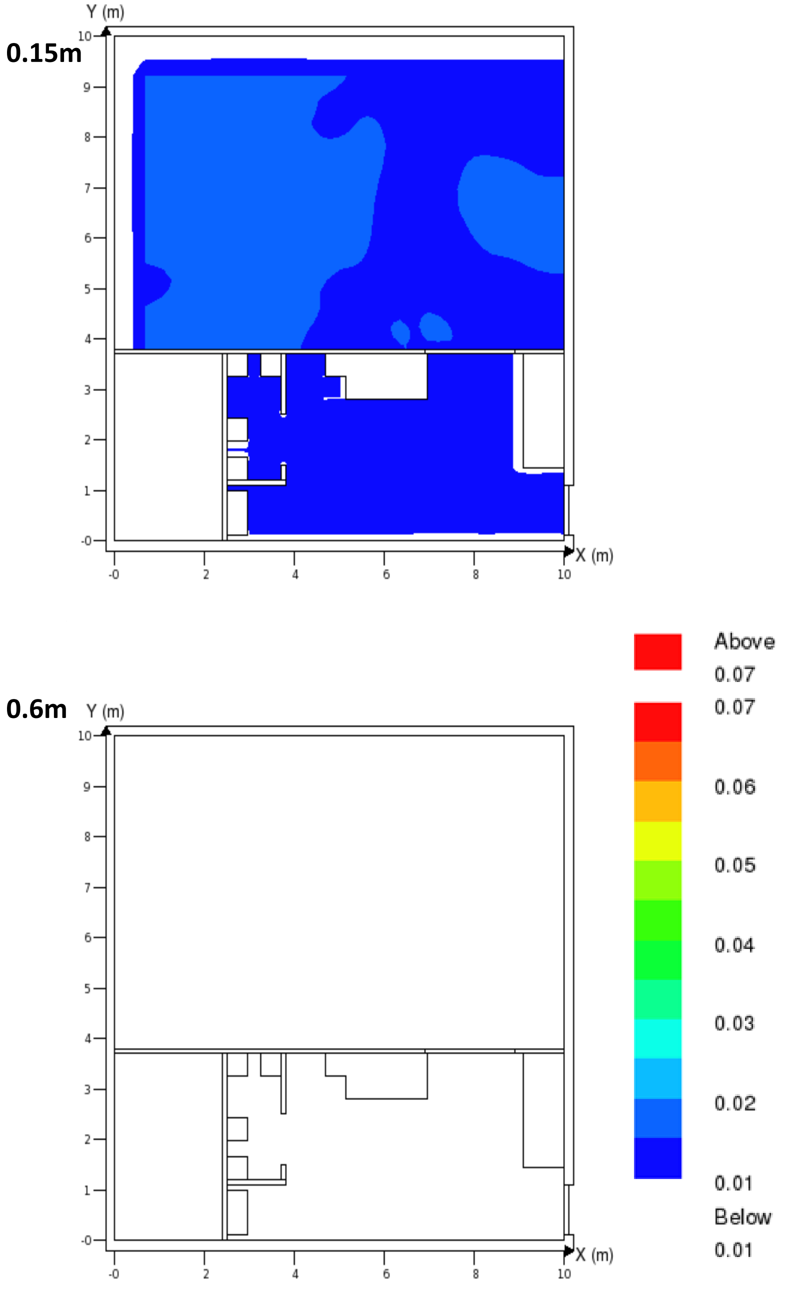


1st floor release : Door open
Case # : 910103
Species : R-1234yf
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed: 35 s
Leak Rate: 0.078 kg/s
Leak Duration: 39 s

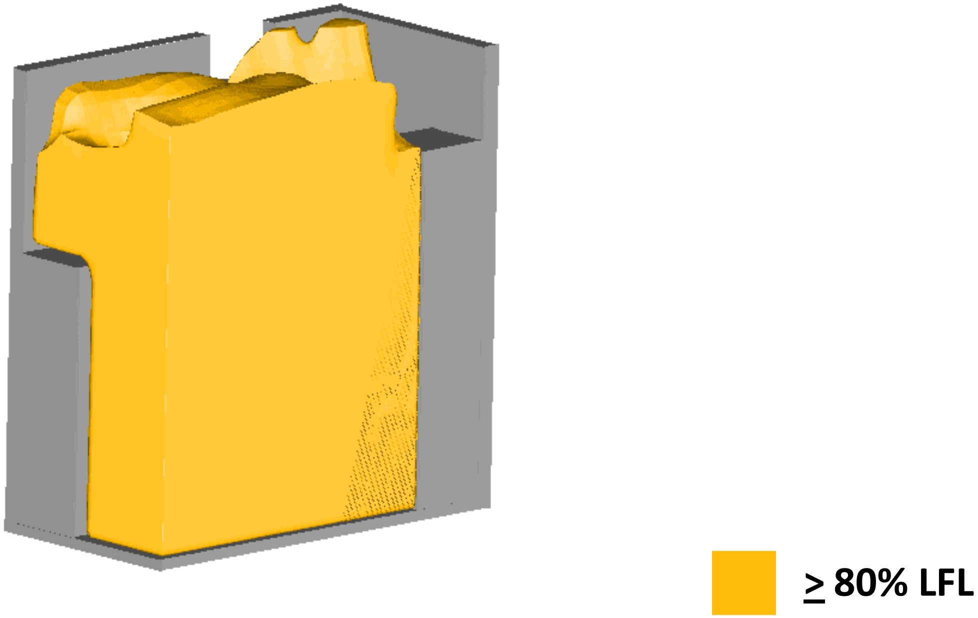


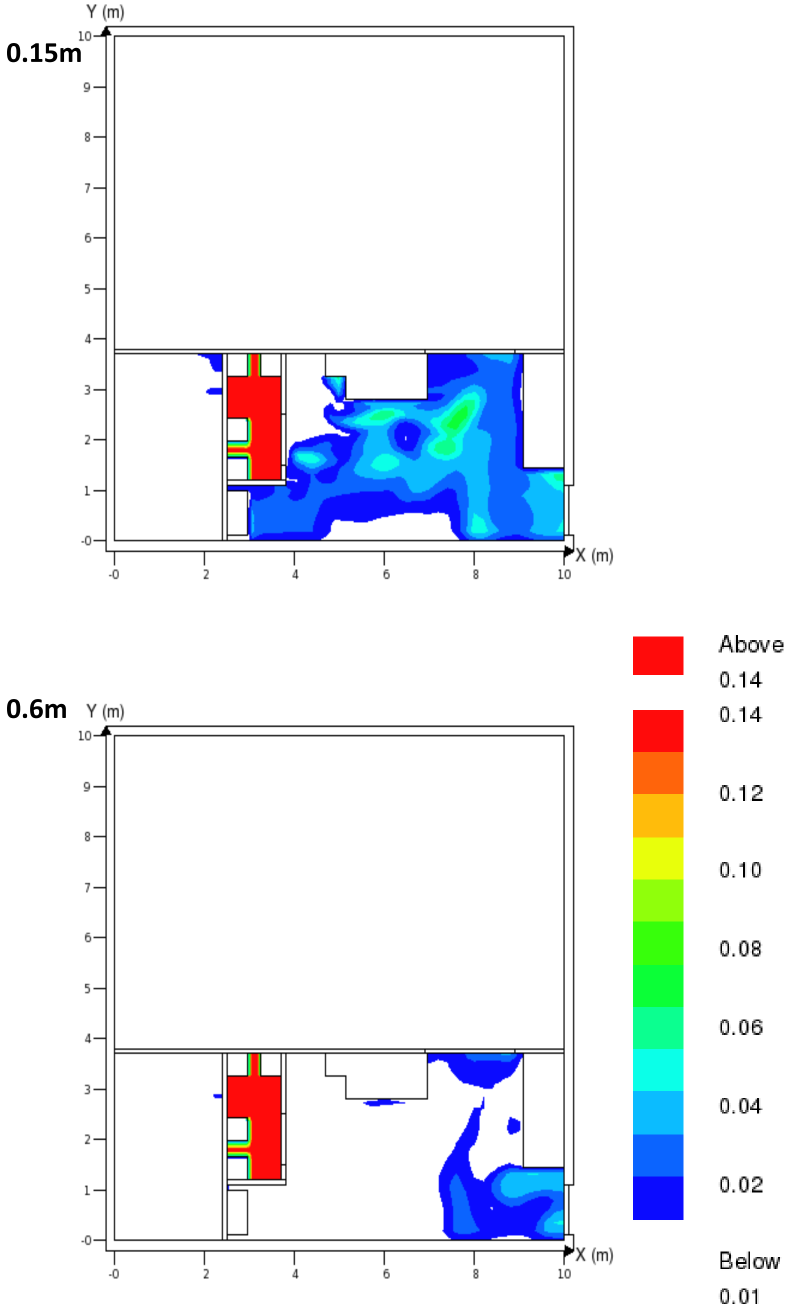


🟧 **≥ 80% LFL**

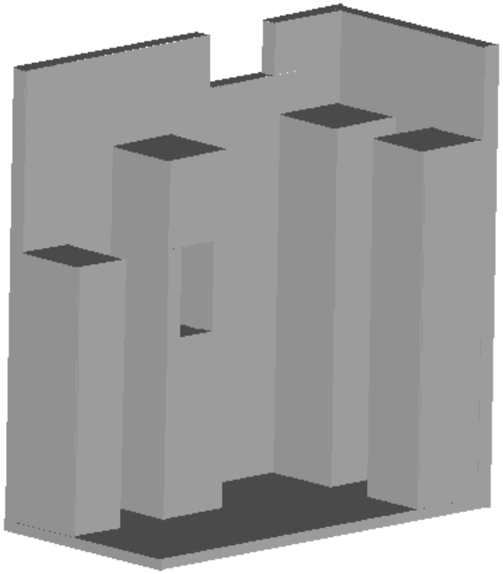


1st floor release : Door open
Case # : 910103
Species : R-1234yf
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed: 810 s
Leak Rate: 0.078 kg/s
Leak Duration: 39 s

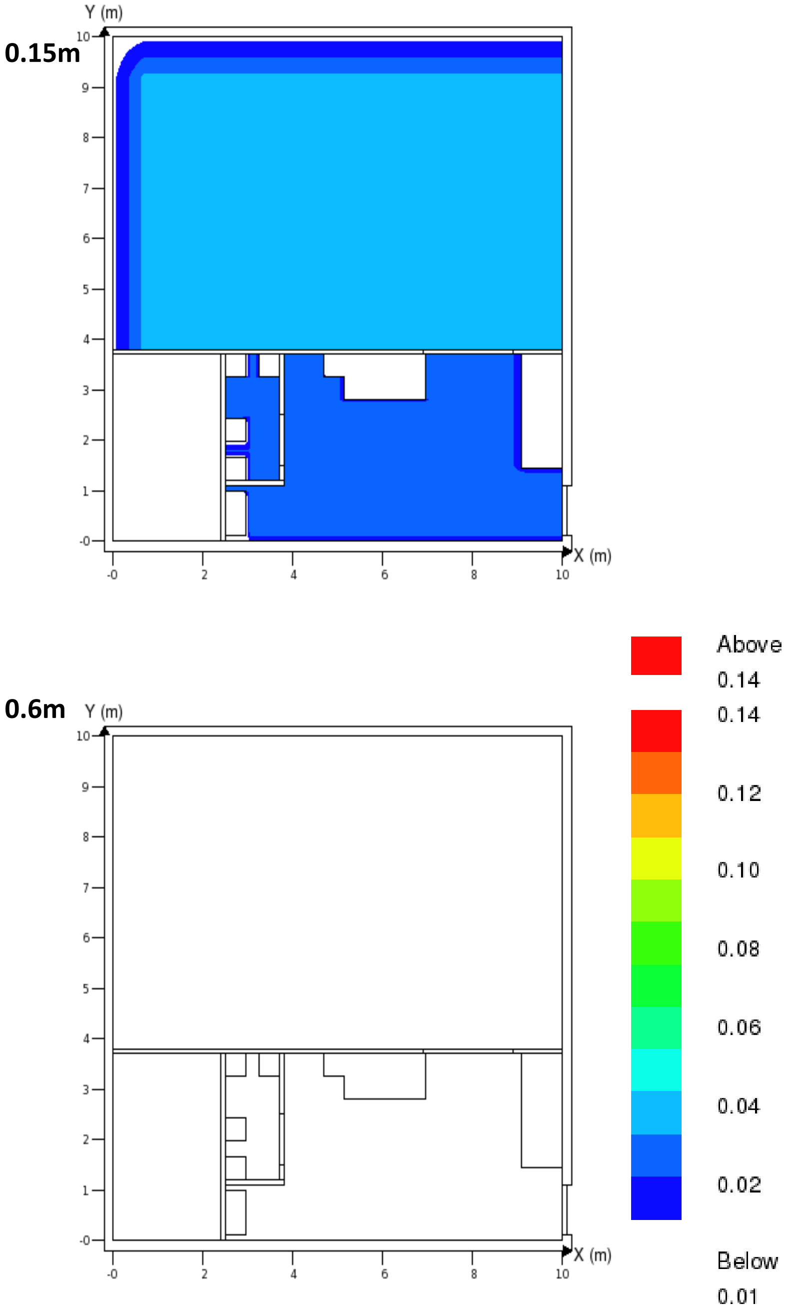




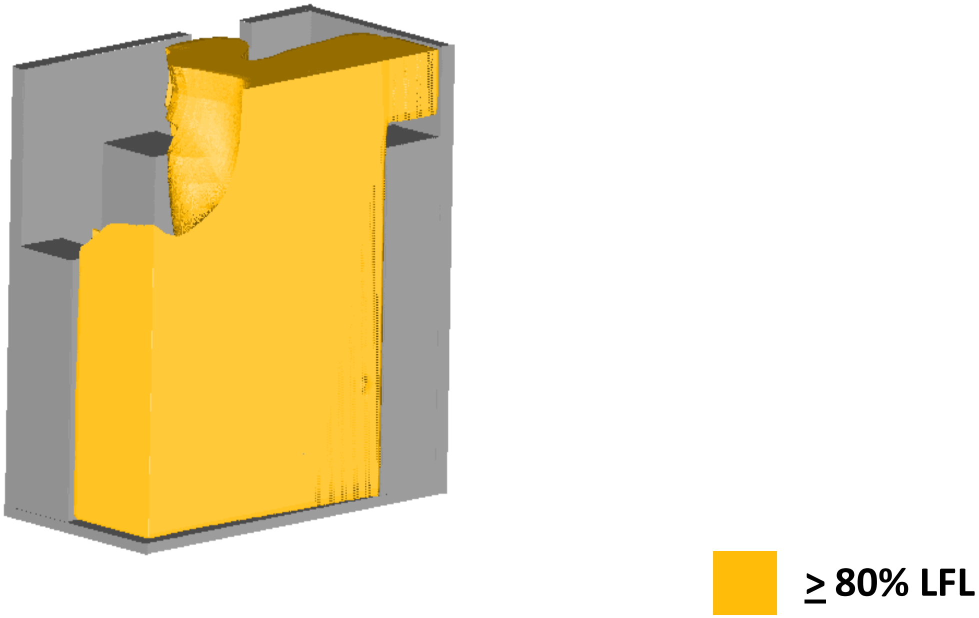
1st floor release : Door closed
Case # : 912101
Species : R-32
3D Volume plot of 80% LFL
2D Contours between 1% and 14%
Time elapsed : 25 s
Leak Rate: 0.17 kg/s
Leak Duration : 18 s

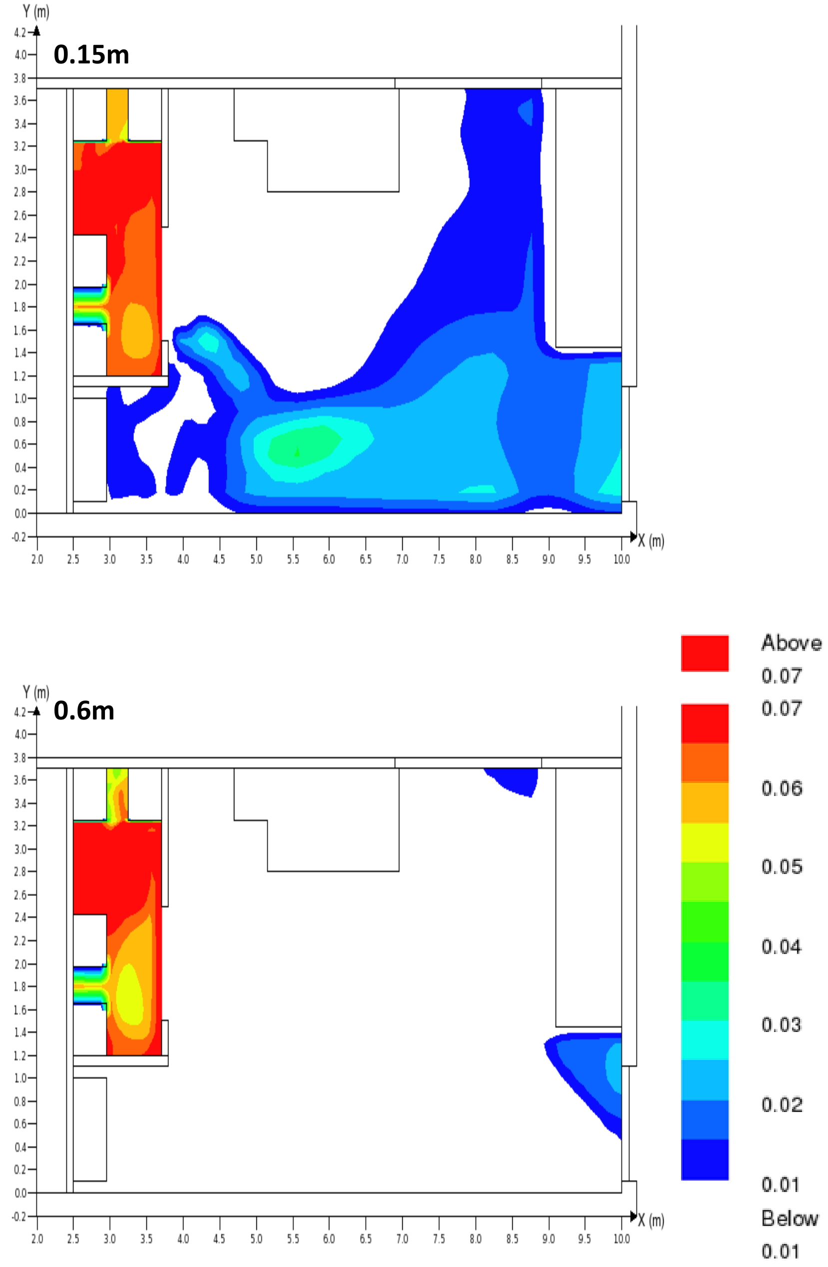


🟧 ≥ 80% LFL

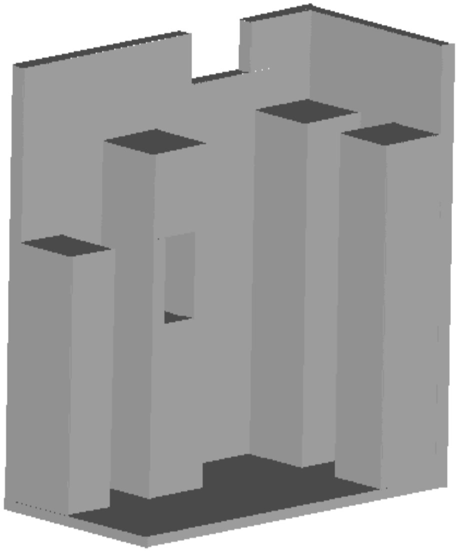


1st floor release : Door closed
Case # : 912101
Species : R-32
3D Volume plot of 80% LFL
2D Contours between 1% and 14%
Time elapsed : 1800 s
Leak Rate: 0.17 kg/s
Leak Duration : 18 s



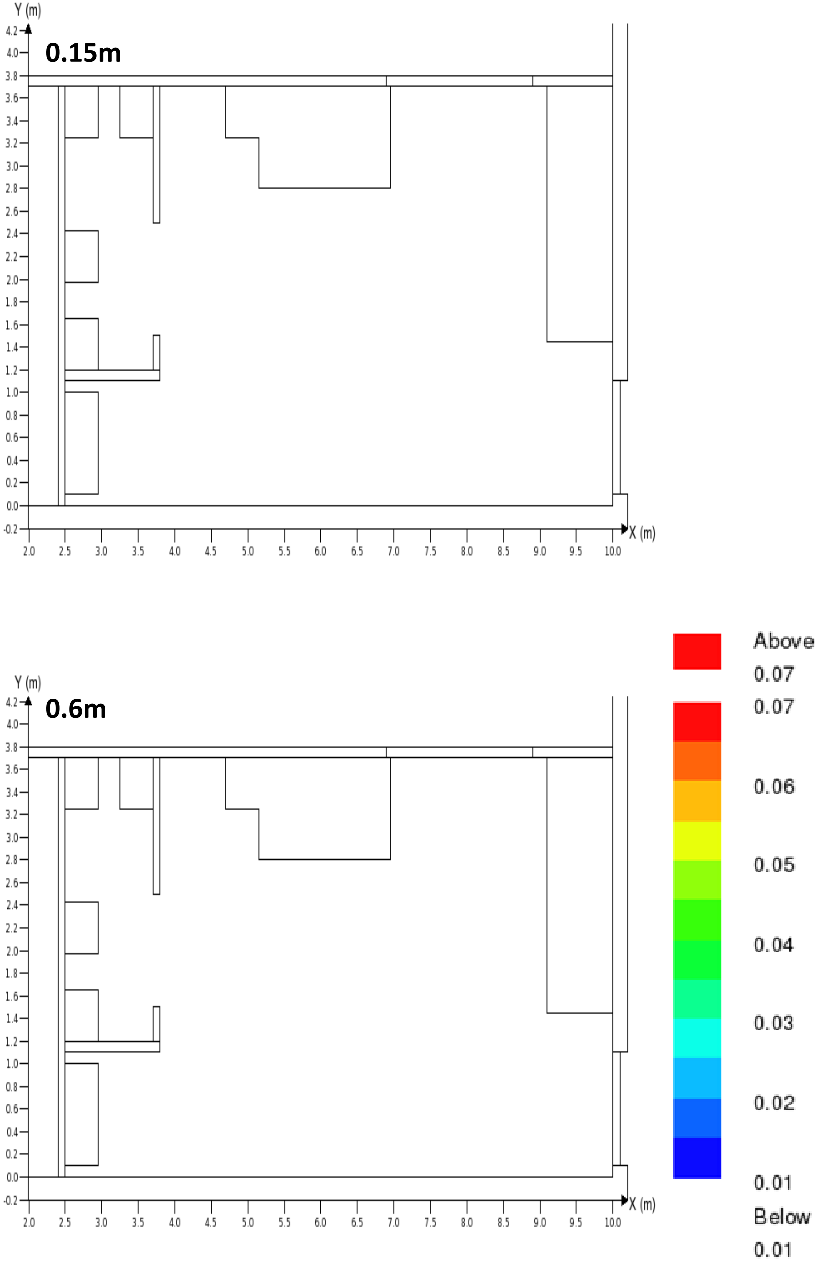


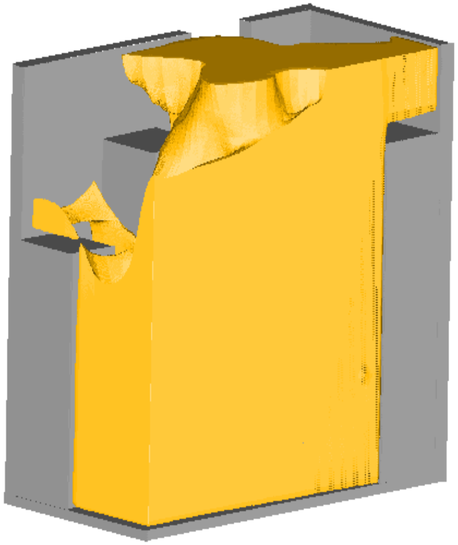
1st floor release : Door closed
Case # : 992102 (revised 912102)
Species : R-1234ze(E)
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed: 35 s
Leak Rate: 0.078 kg/s
Leak Duration: 39 s



🟧 **≥ 80% LFL**

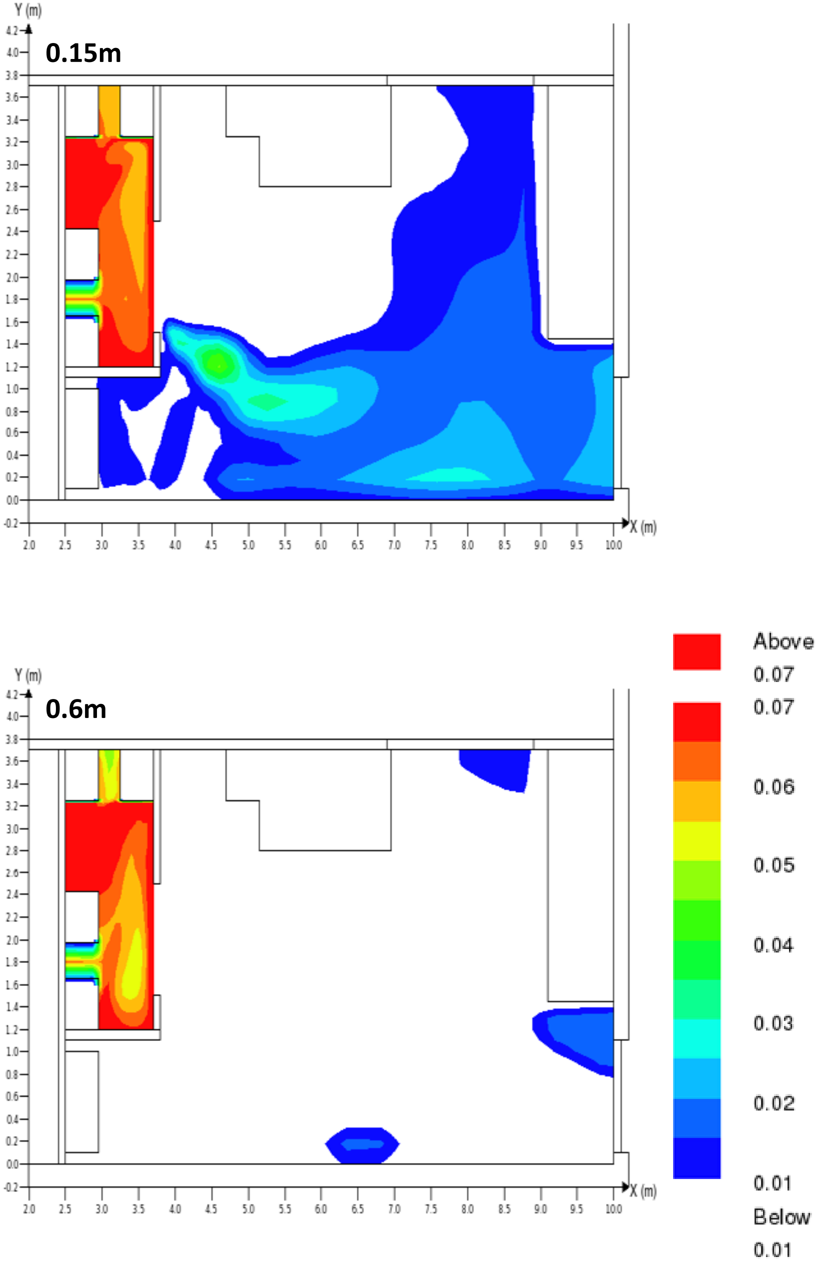
1st floor release : Door closed
Case # : 992102 (revised 912102)
Species : R-1234ze(E)
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed: 1800 s
Leak Rate: 0.078 kg/s
Leak Duration: 39 s

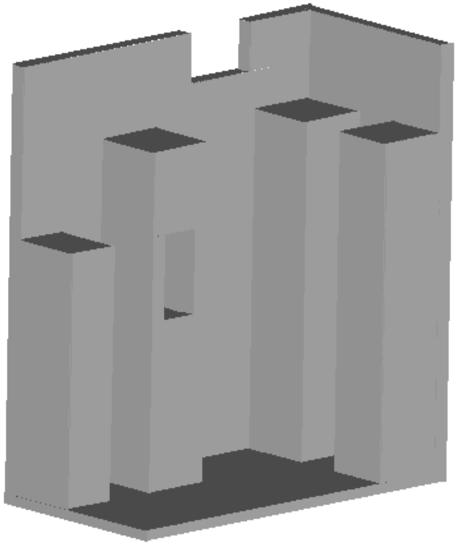




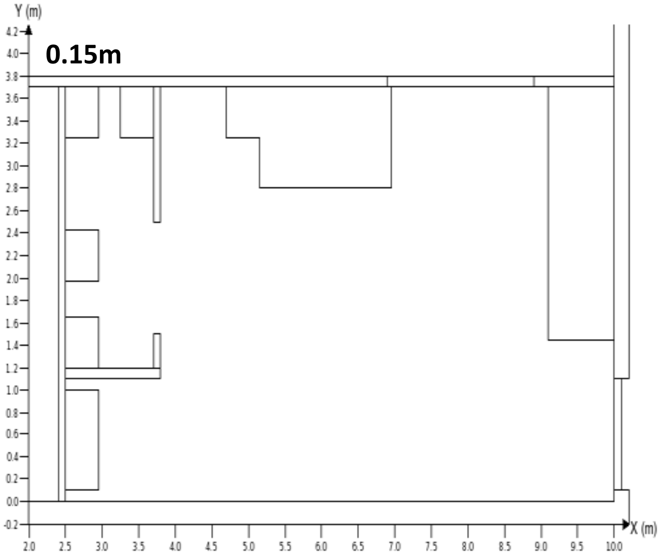
🟧 **≥ 80% LFL**

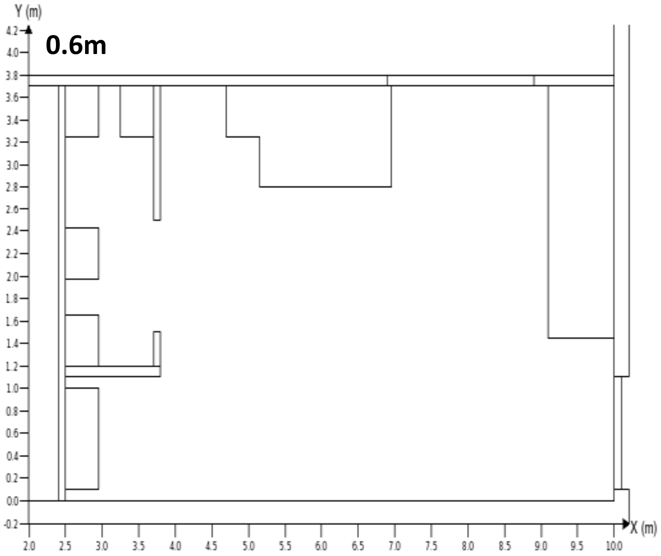
1st floor release : Door closed
Case # : 992103 (revised 912103)
Species : R-1234yf
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed: 35 s
Leak Rate: 0.078 kg/s
Leak Duration: 39 s

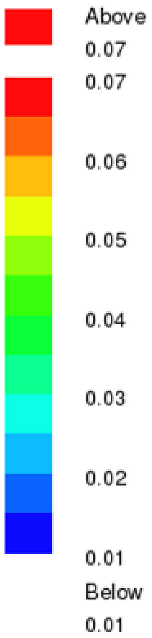




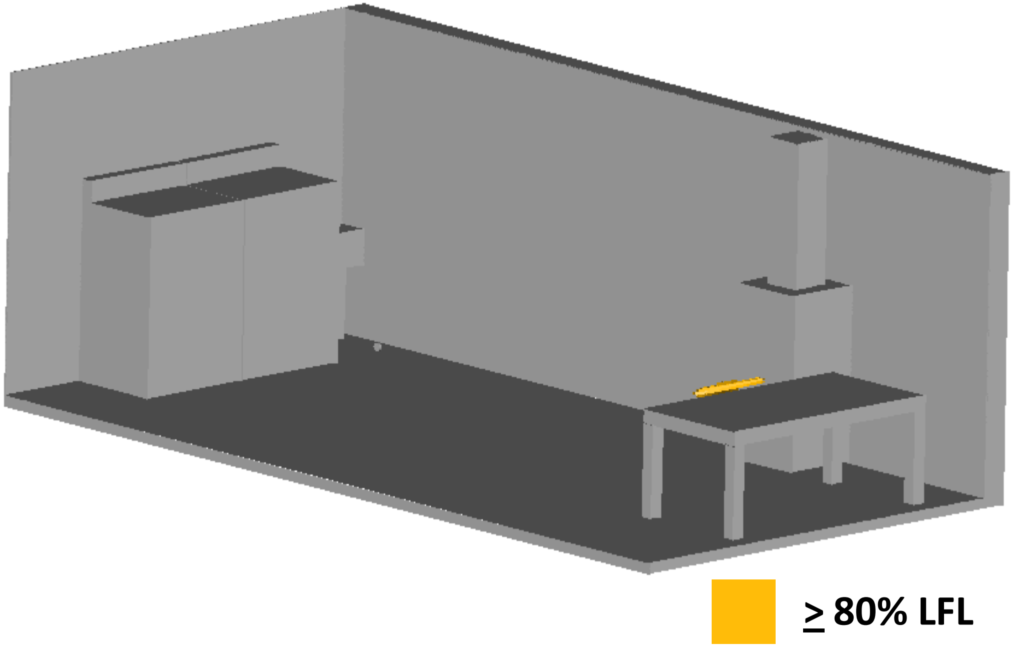
🟧 **≥ 80% LFL**

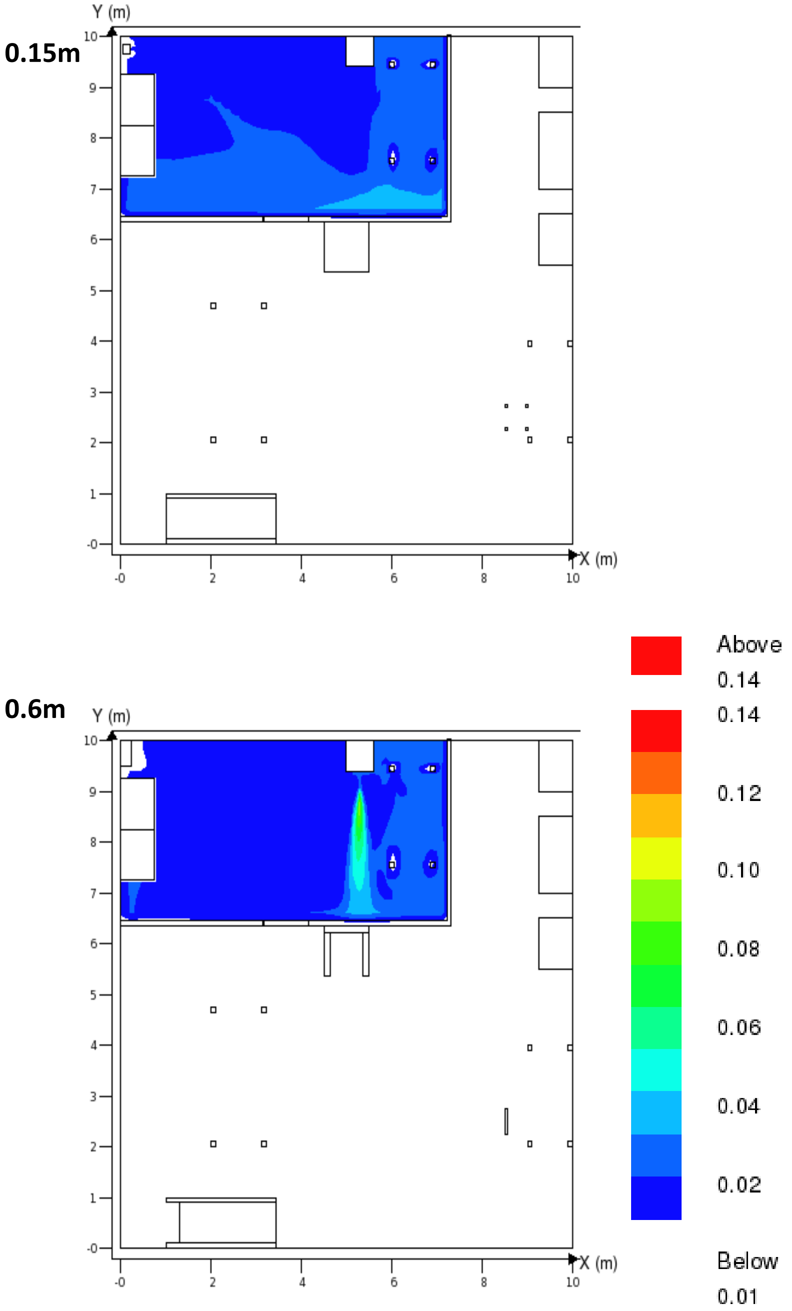






1st floor release : Door closed
Case # : 992103 (revised 912103)
Species : R-1234yf
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed: 1800 s
Leak Rate: 0.078 kg/s
Leak Duration: 39 s





Basement release

Case # : 910301

Species : R-32

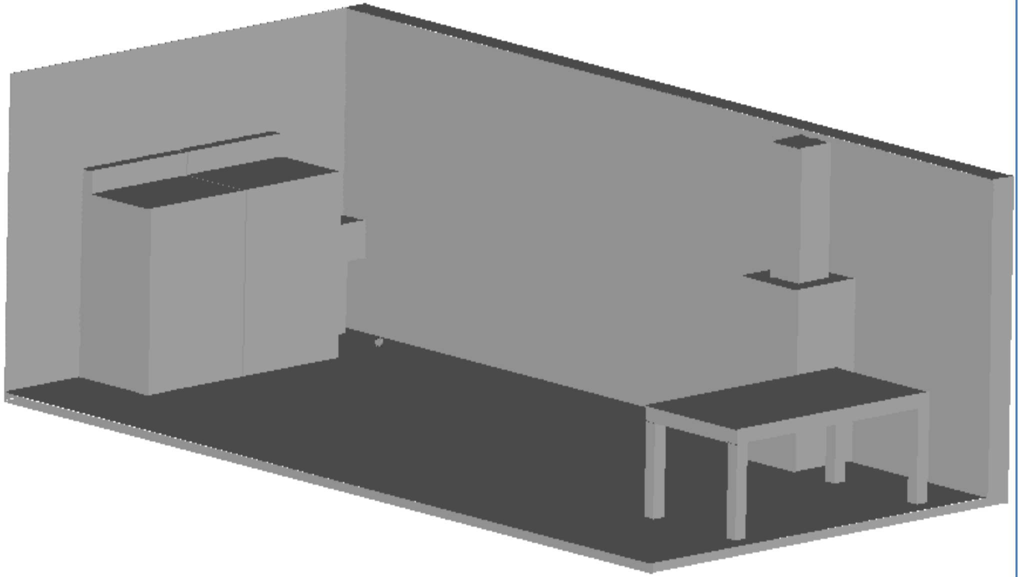
2D Volume plot of 80% LFL

3D Contours between 1% and 14%

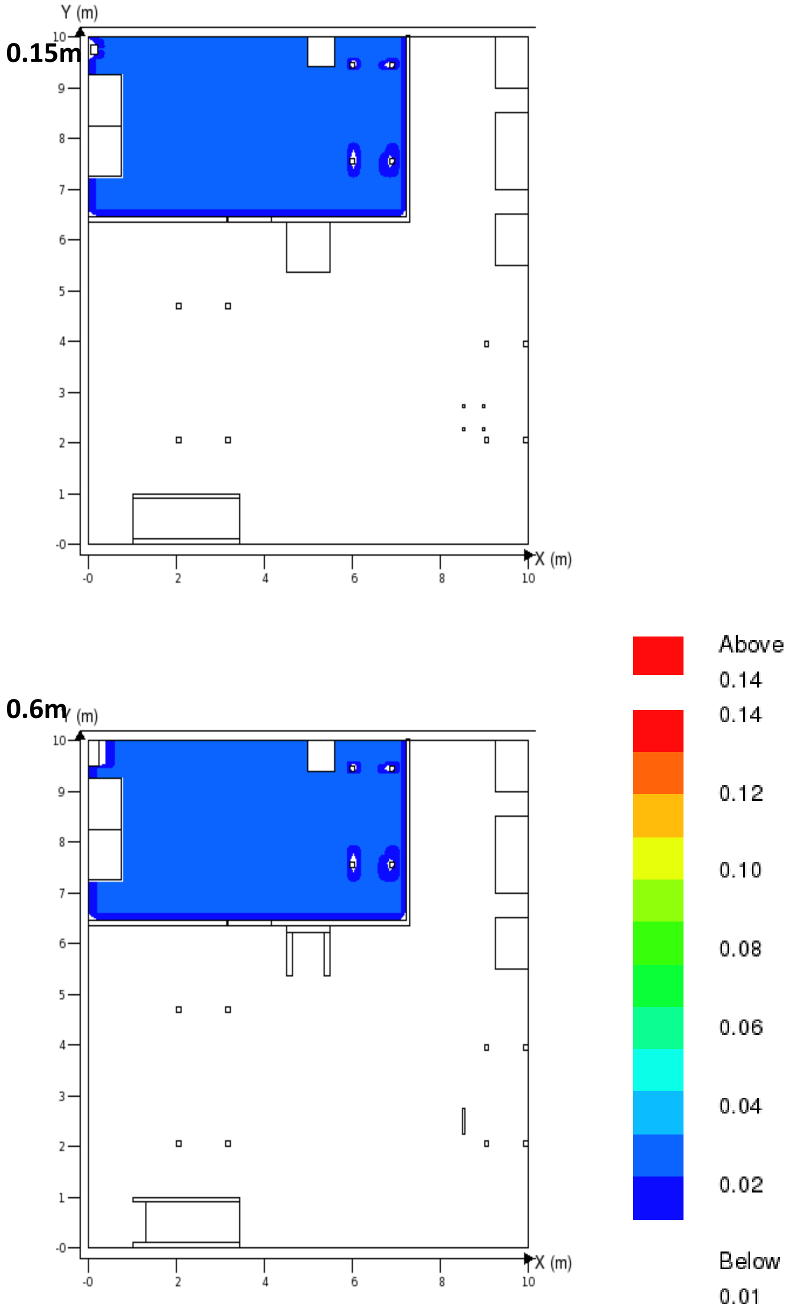
Time elapsed: 15 s

Leak Rate: 0.159 kg/s

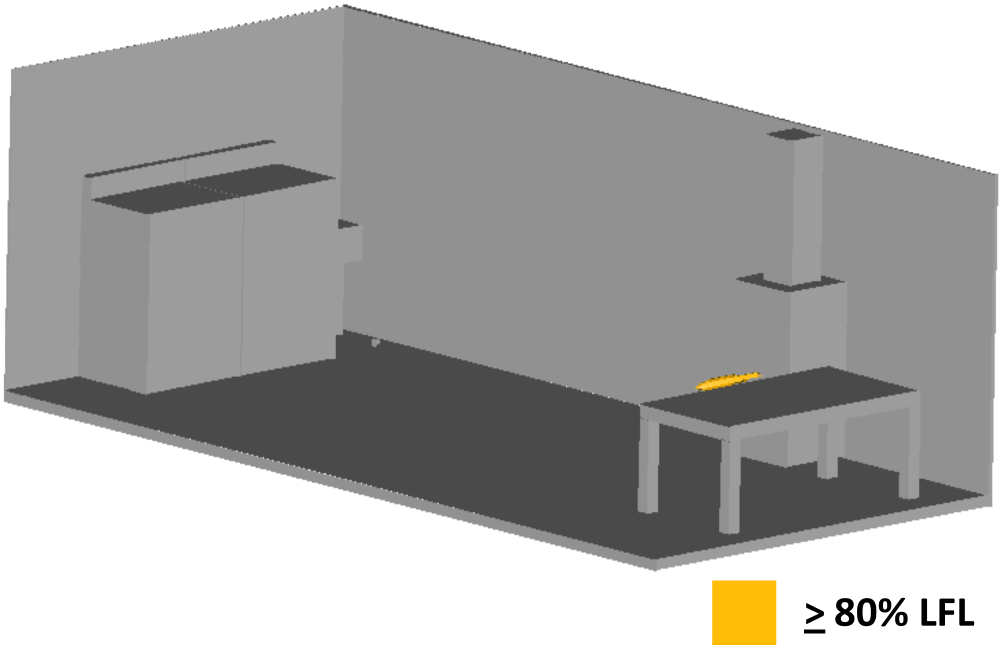
Leak Duration: 19.2 s

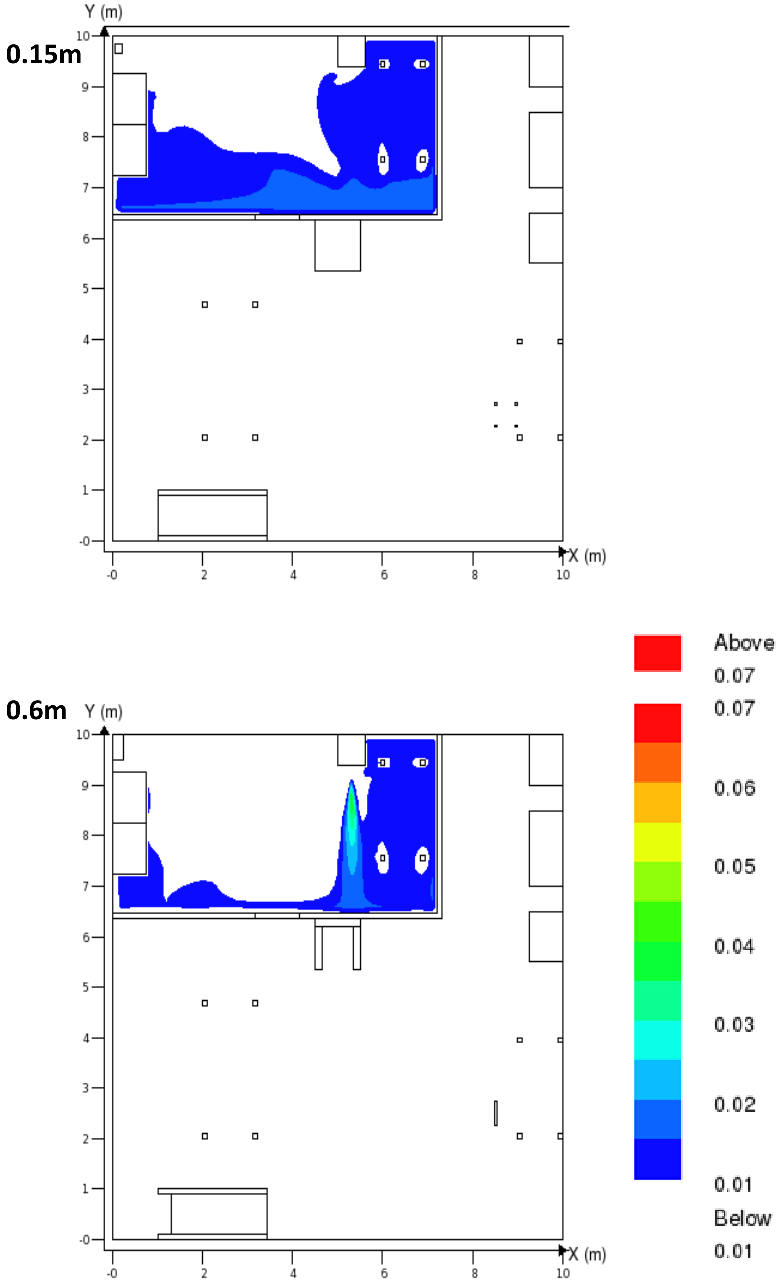


🟧 **≥ 80% LFL**

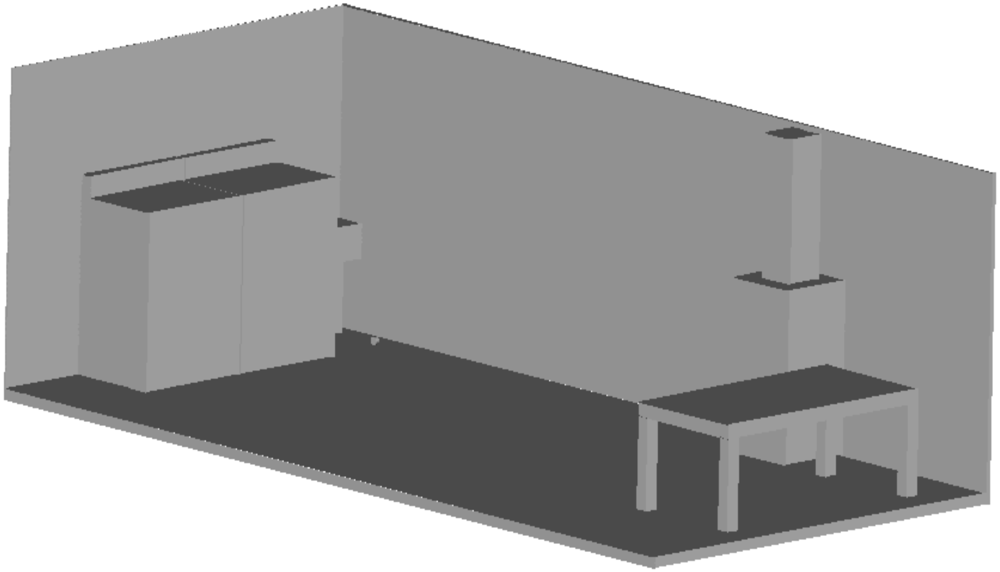


Basement release
Case # : 910301
Species : R-32
3D Volume plot of 80% LFL
2D Contours between 1% and 14%
Time elapsed: 1800 s
Leak Rate: 0.159 kg/s
Leak Duration: 19.2 s





Basement release
Case # : 910302
Species : R-1234ze(E)
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed: 30 s
Leak Rate: 0.094 kg/s
Leak Duration: 32.4 s



🟧 **≥ 80% LFL**

Basement release

Case # : 910302

Species : R-1234ze(E)

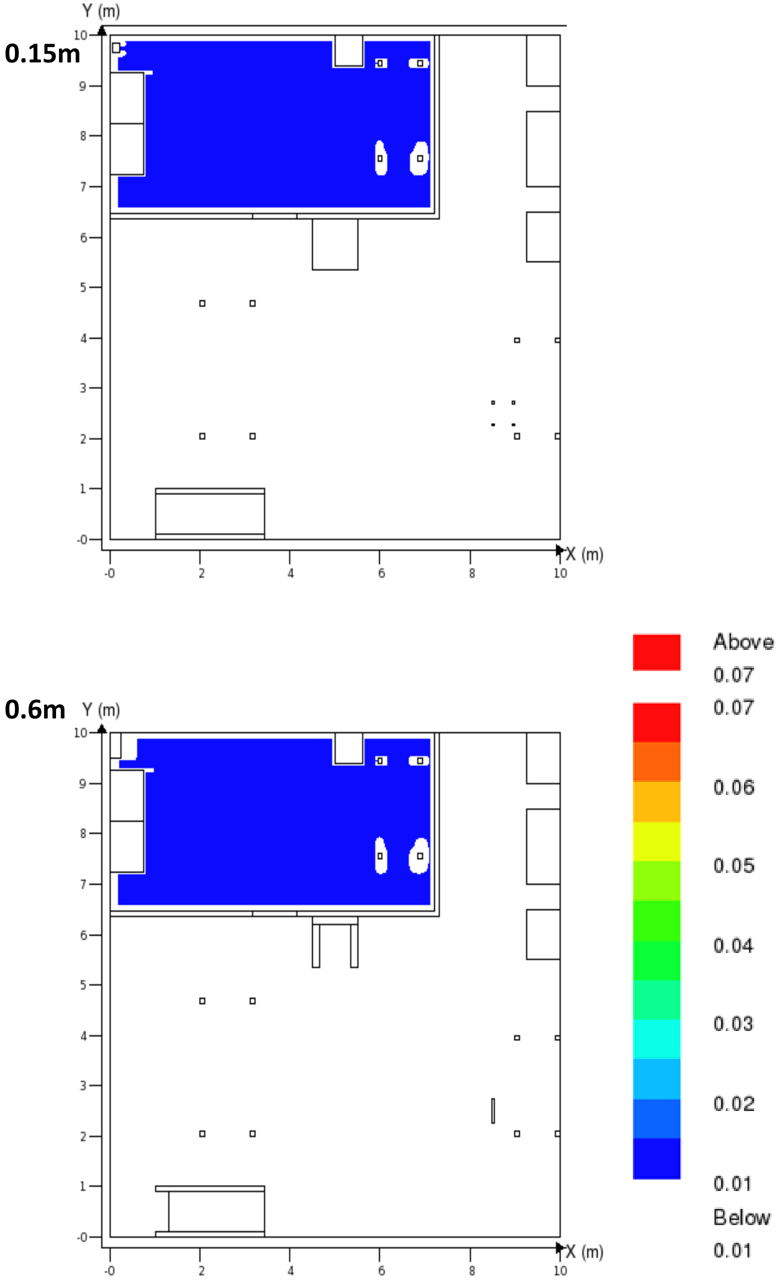
3D Volume plot of 80% LFL

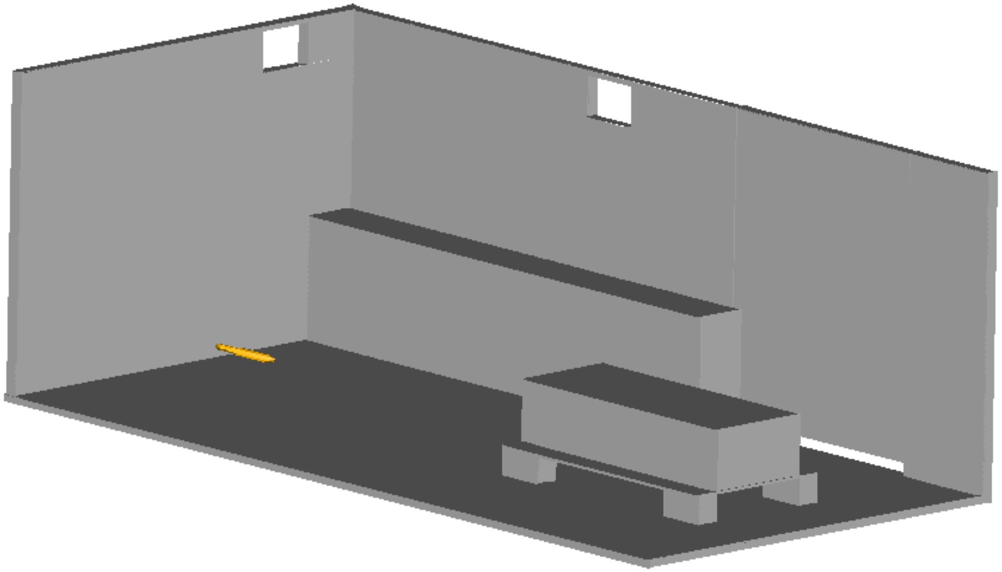
2D Contours between 1% and 7%

Time elapsed: 1800 s

Leak Rate: 0.094 kg/s

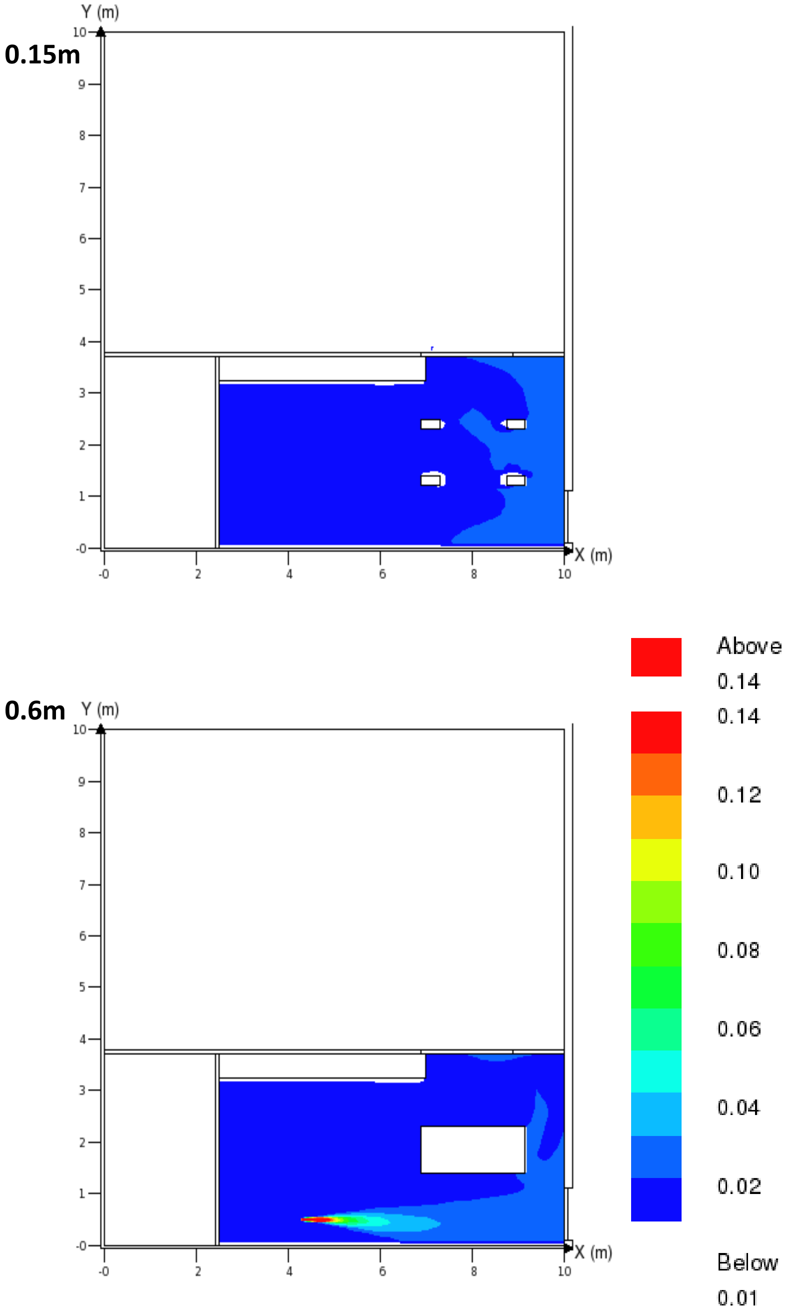
Leak Duration: 32.4 s

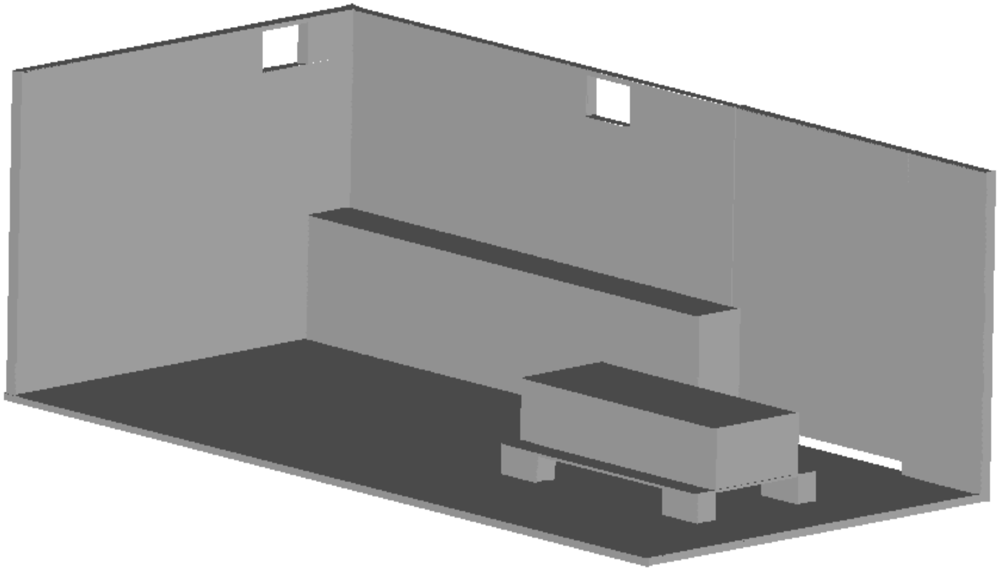




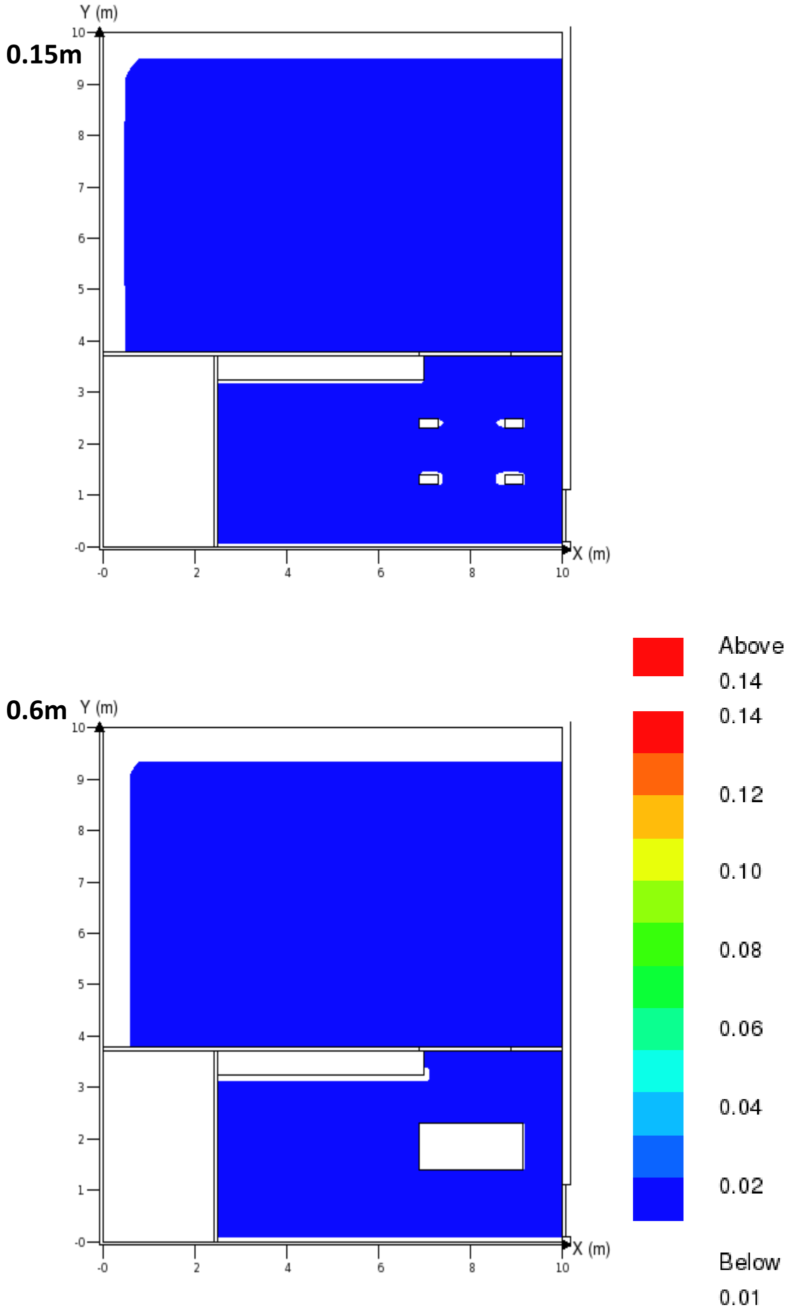
🟧 ≥ 80% LFL

Garage release
Case # : 910201
Species : R-32
3D Volume plot of 80% LFL
2D Contours between 1% and 14%
Time elapsed : 20 s
Leak Rate: 0.146 kg/s
Leak Duration : 21 s

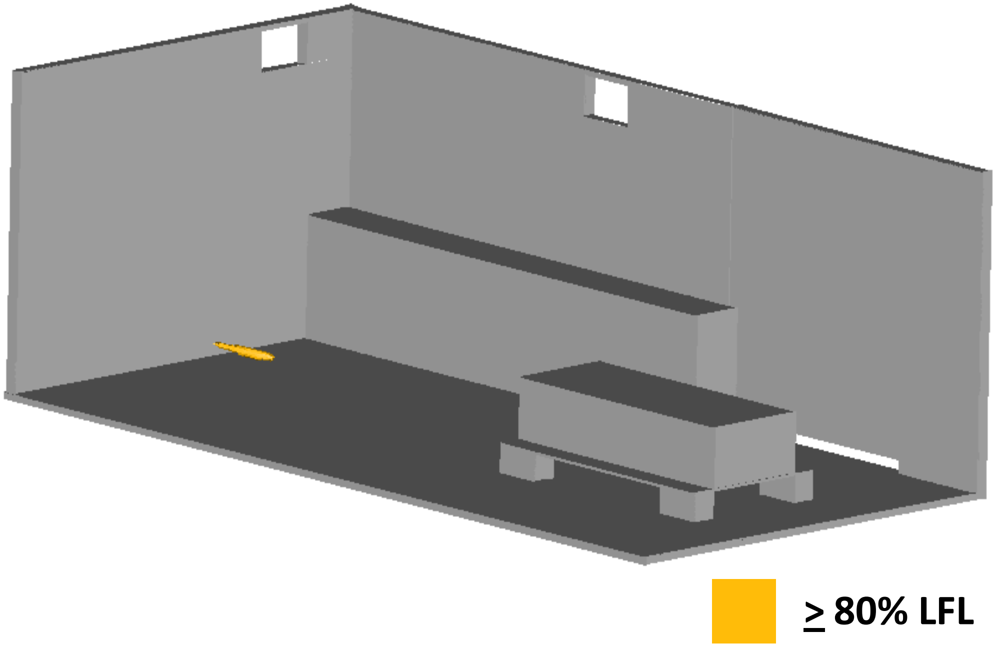


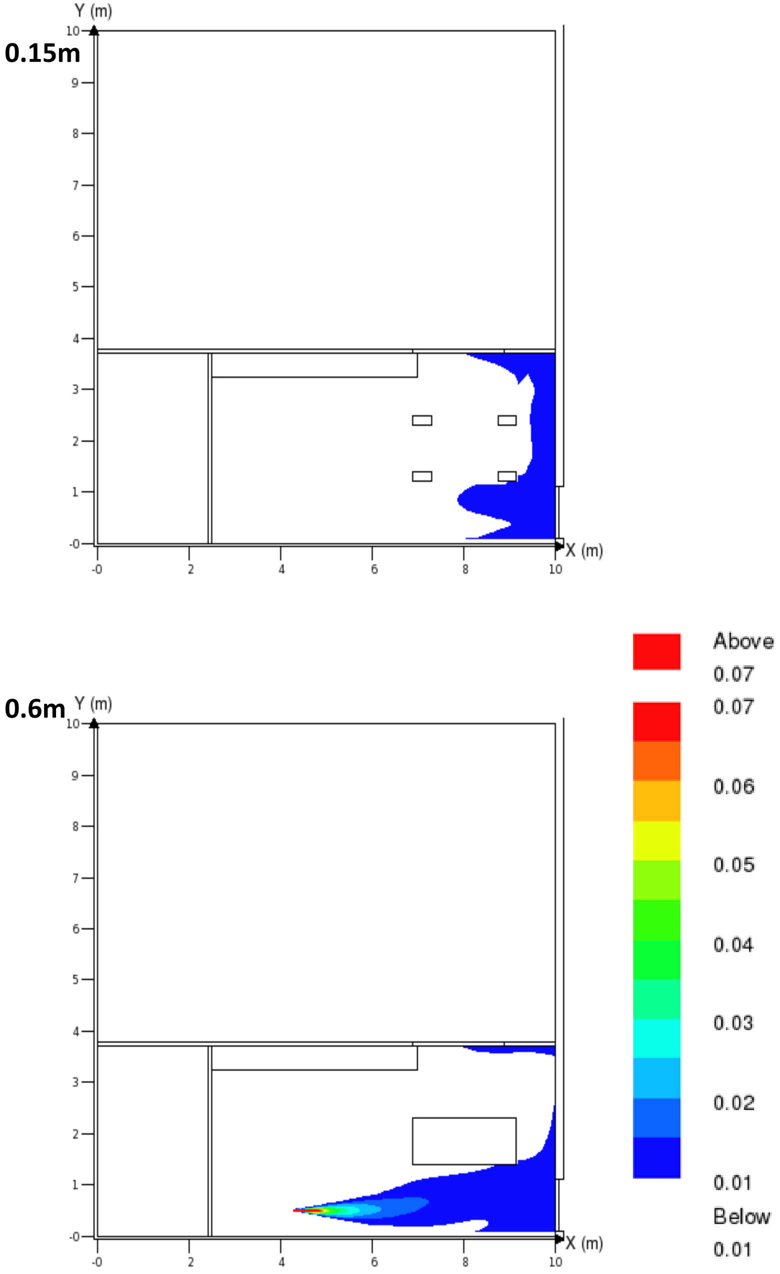


🟧 ≥ 80% LFL



Garage release
Case # : 910201
Species : R-32
3D Volume plot of 80% LFL
2D Contours between 1% and 14%
Time elapsed : 1800 s
Leak Rate: 0.146 kg/s
Leak Duration : 21 s





Garage release

Case # : 910202

Species : R-1234ze(E)

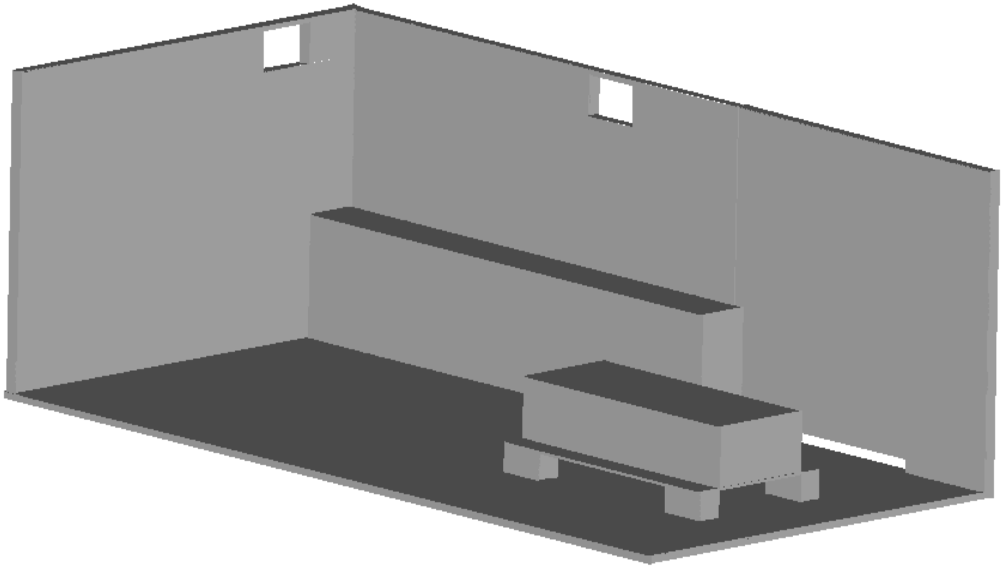
3D Volume plot of 80% LFL

2D Contours between 1% and 7%

Time elapsed: 30 s

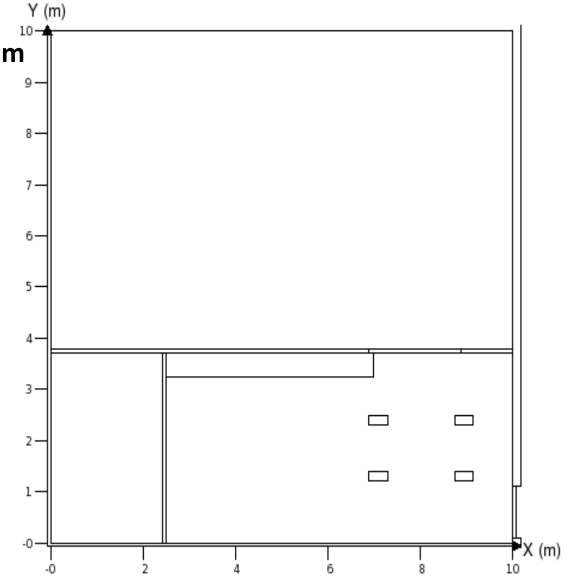
Leak Rate: 0.096 kg/s

Leak Duration: 31.8 s

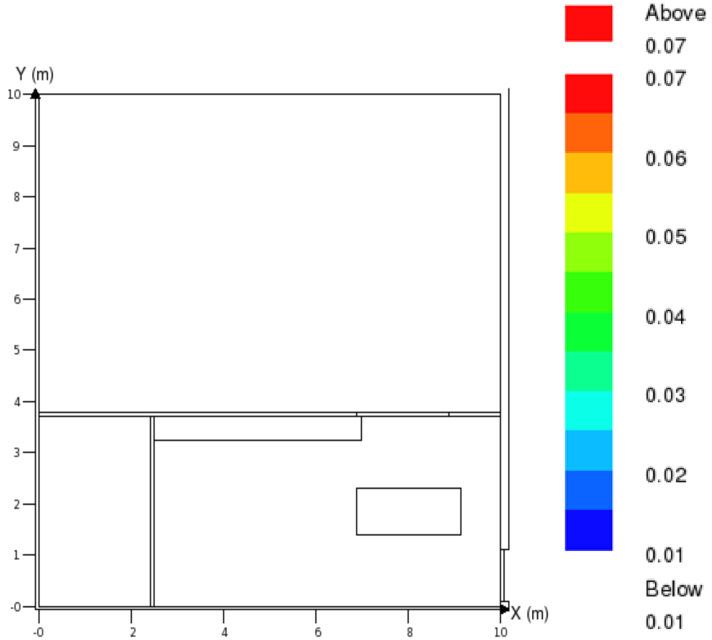


🟧 ≥ 80% LFL

0.15m



0.6m



Garage release

Case # : 910202

Species : R-1234ze(E)

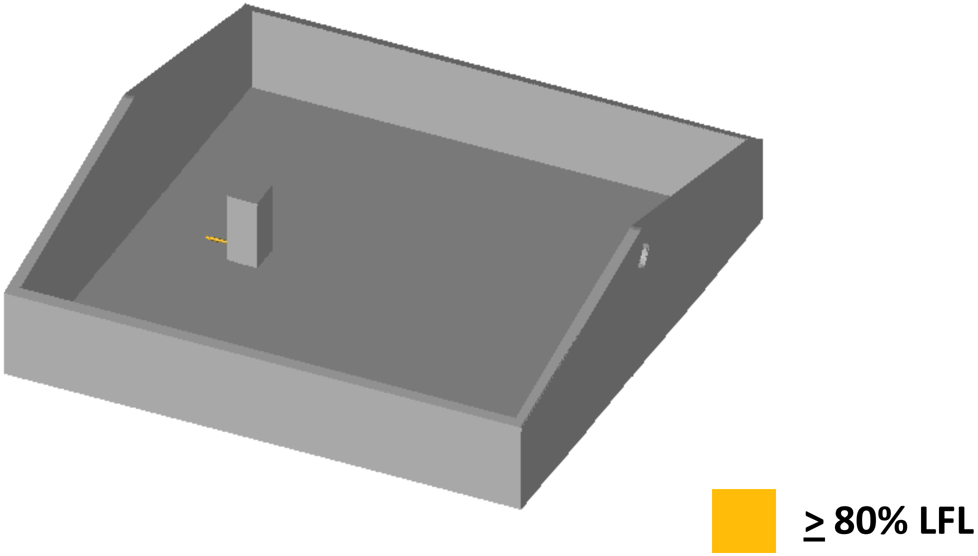
3D Volume plot of 80% LFL

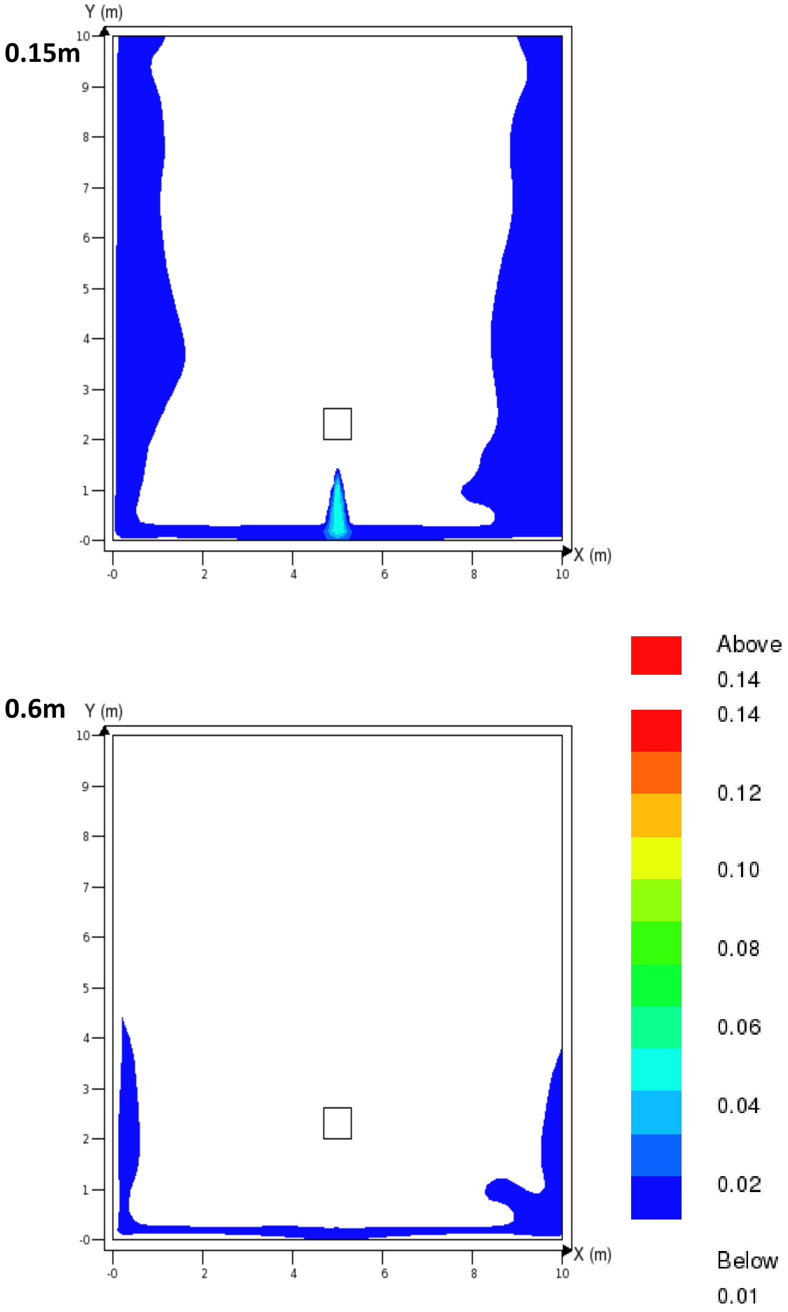
2D Contours between 1% and 7%

Time elapsed: 1710 s

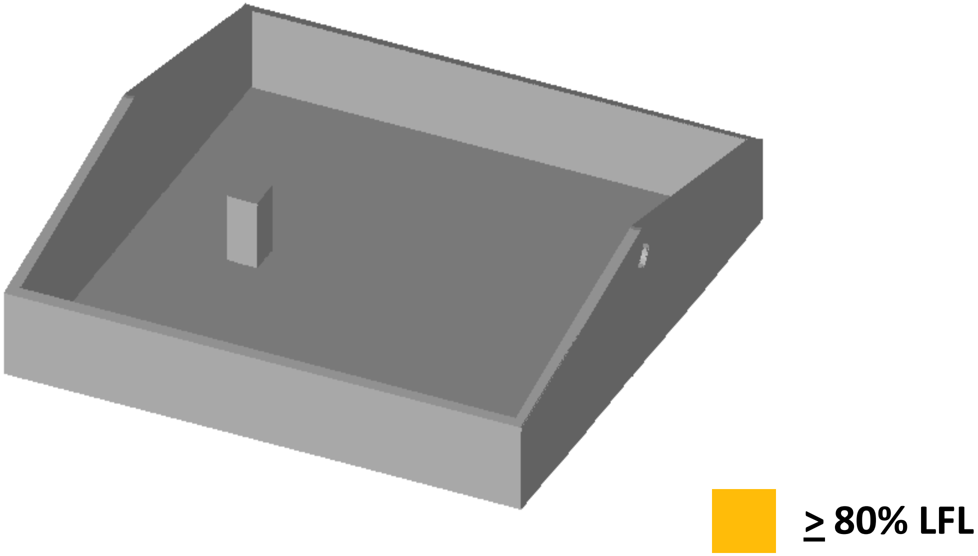
Leak Rate: 0.096 kg/s

Leak Duration: 31.8 s

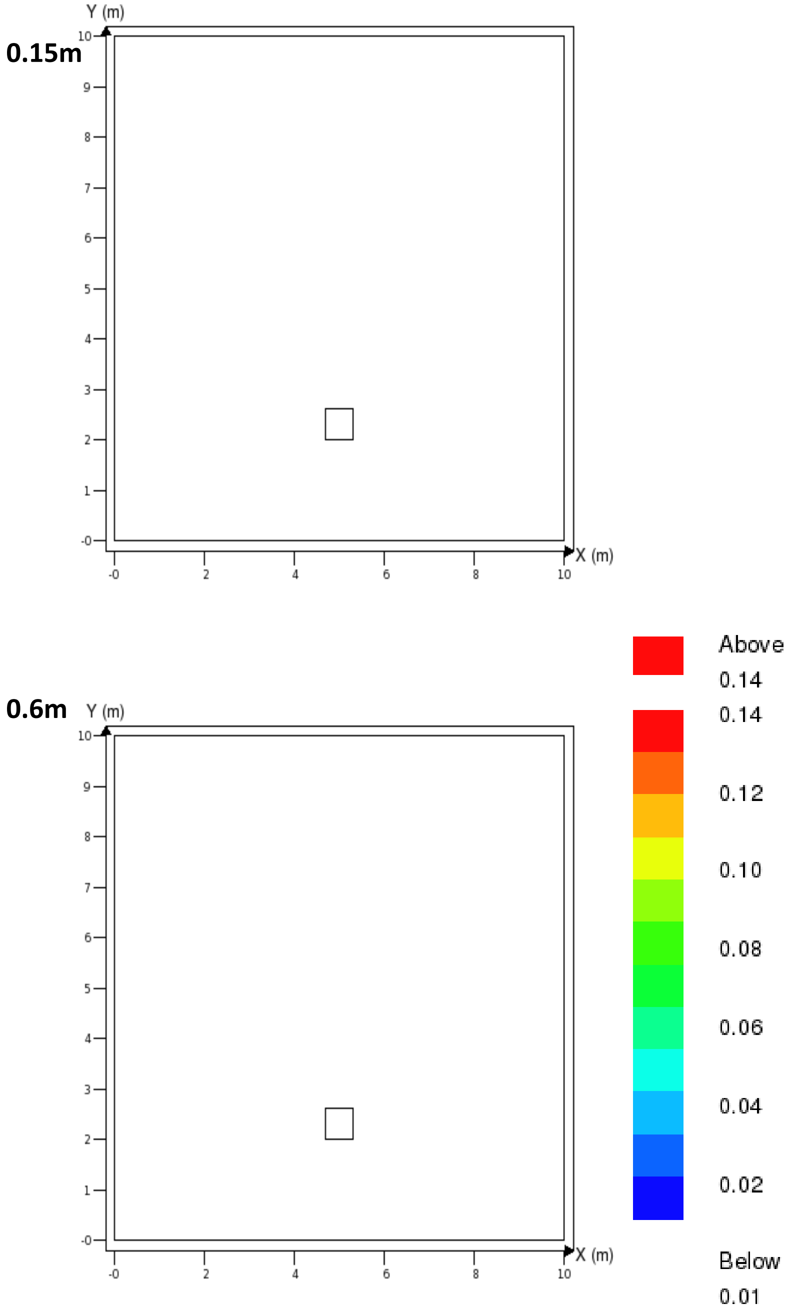


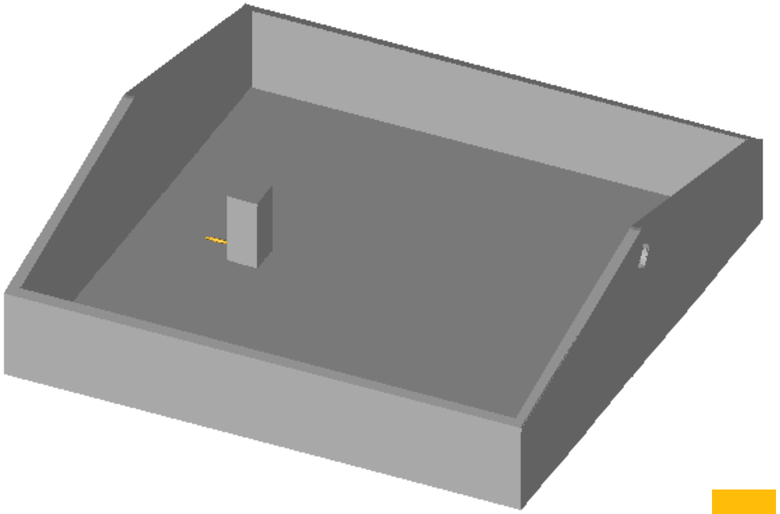


Attic release
Case # : 910401
Species : R-32
3D Volume plot of 80% LFL
2D Contours between 1% and 14%
Time elapsed: 20 s
Leak Rate: 0.146 kg/s
Leak Duration: 21 s



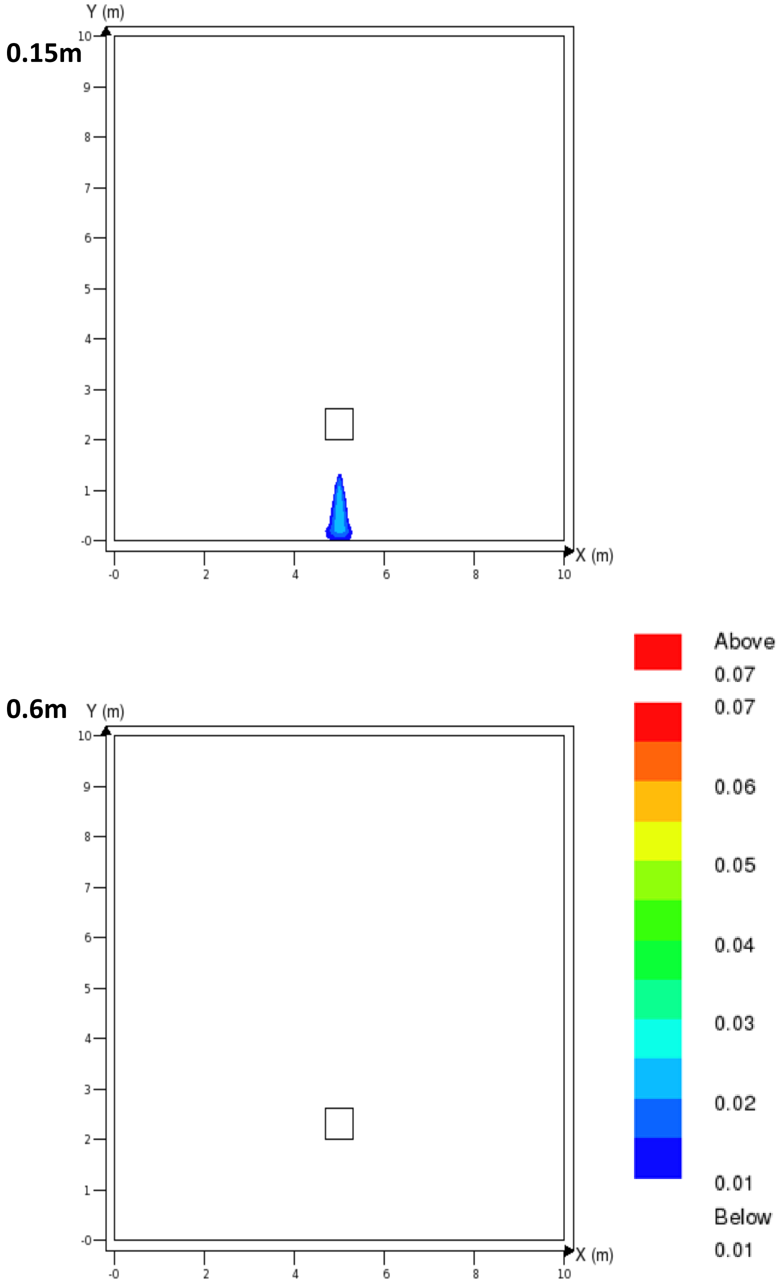
Attic release
Case # : 910401
Species : R-32
3D Volume plot of 80% LFL
2D Contours between 1% and 14%
Time elapsed: 1320 s
Leak Rate: 0.146 kg/s
Leak Duration: 21 s

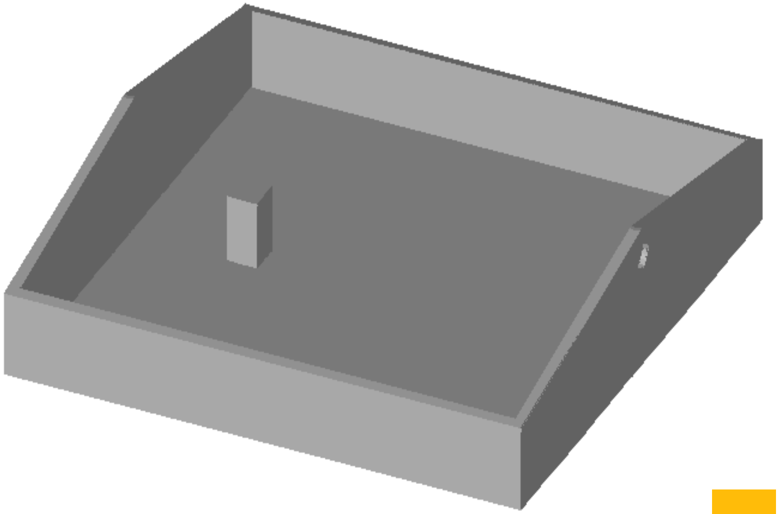




🟧 ≥ 80% LFL

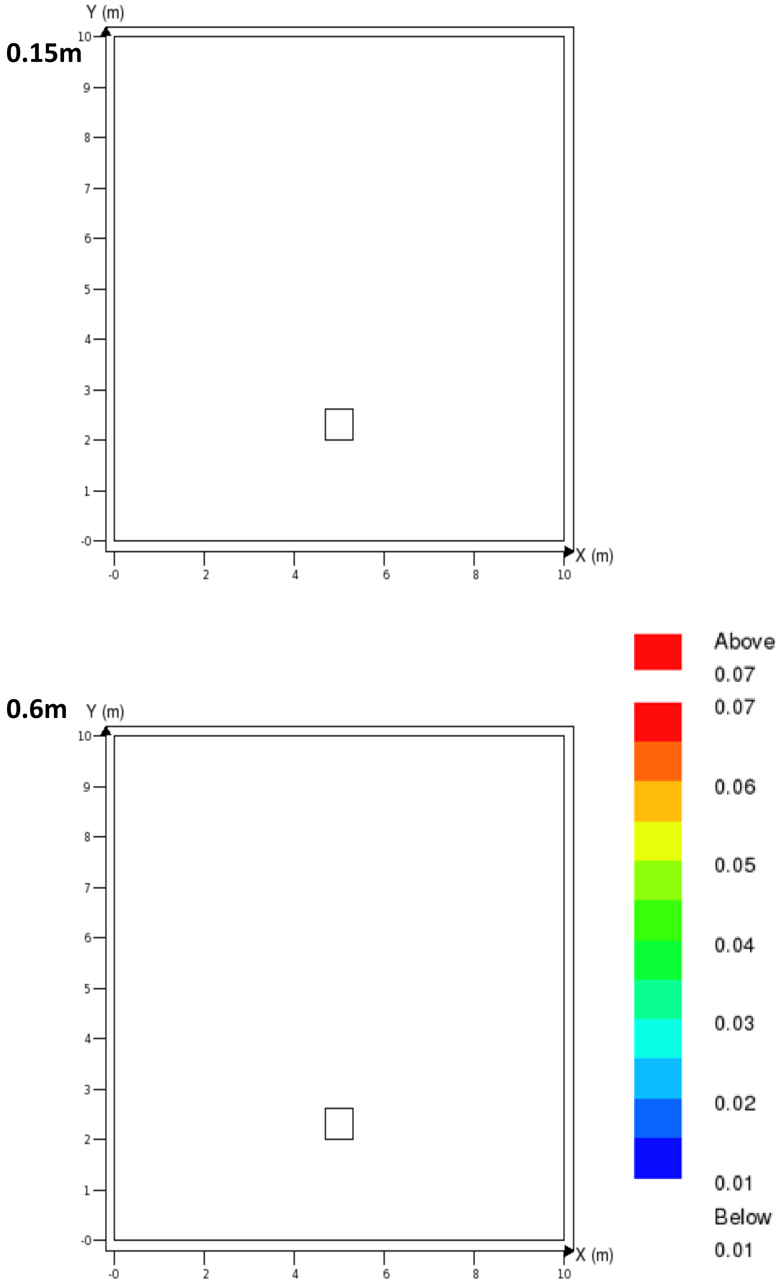
Attic release
Case # : 910402
Species : R-1234ze(E)
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed: 30 s
Leak Rate: 0.096 kg/s
Leak Duration: 31.8 s

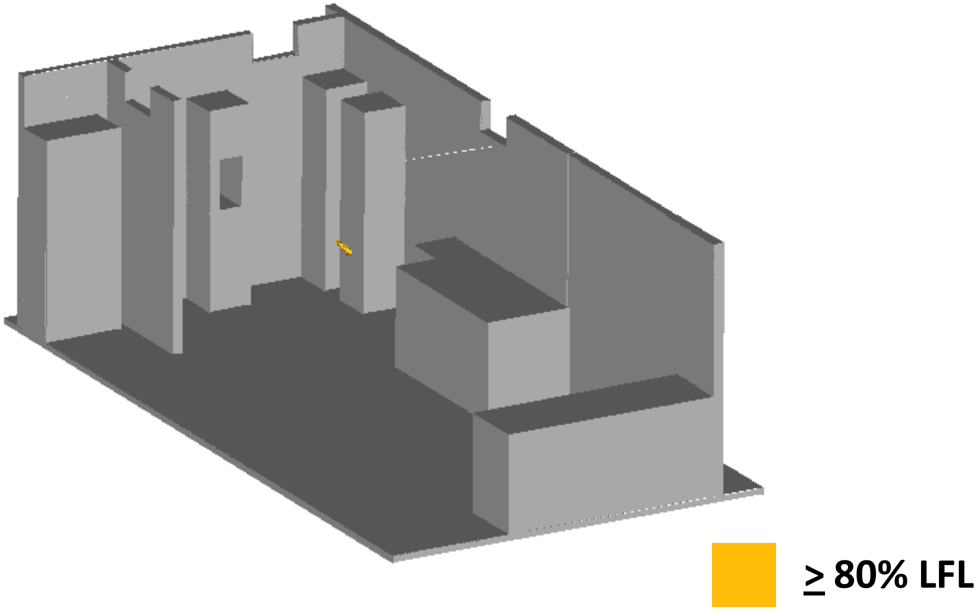


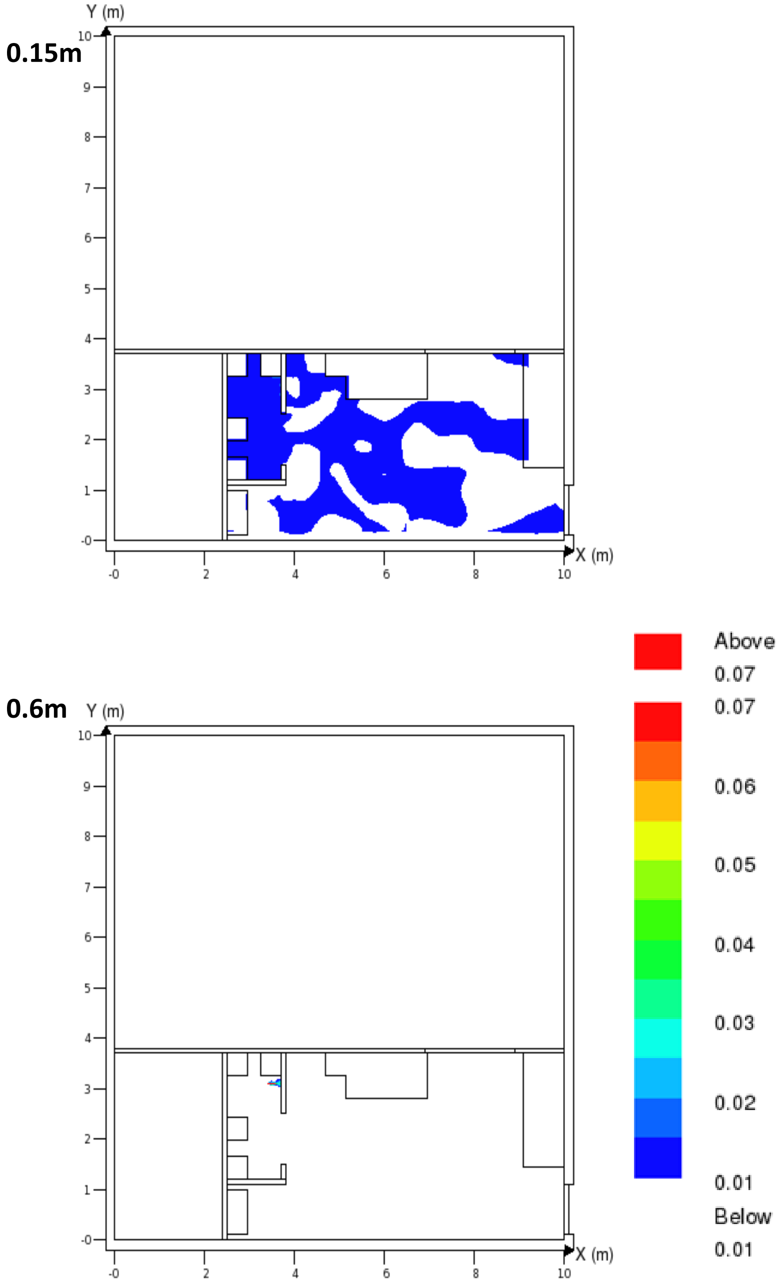


🟧 ≥ 80% LFL

Attic release
Case # : 910402
Species : R-1234ze(E)
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed: 1230 s
Leak Rate: 0.096 kg/s
Leak Duration: 31.8 s







1st floor release : Door open

Case # : 210111

Species : R-1234ze(E)

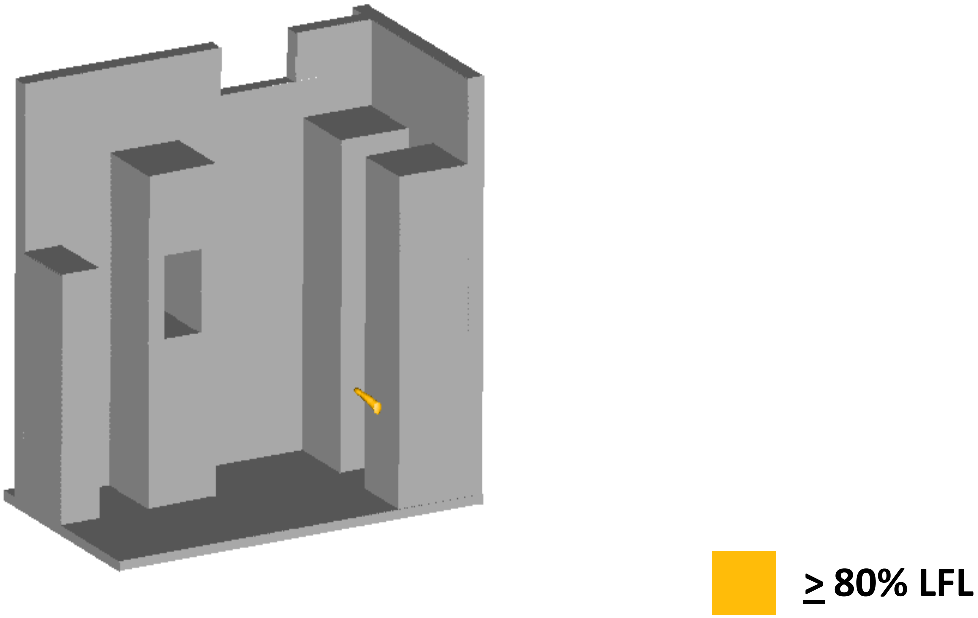
3D Volume plot of 80% LFL

2D Contours between 1% and 7%

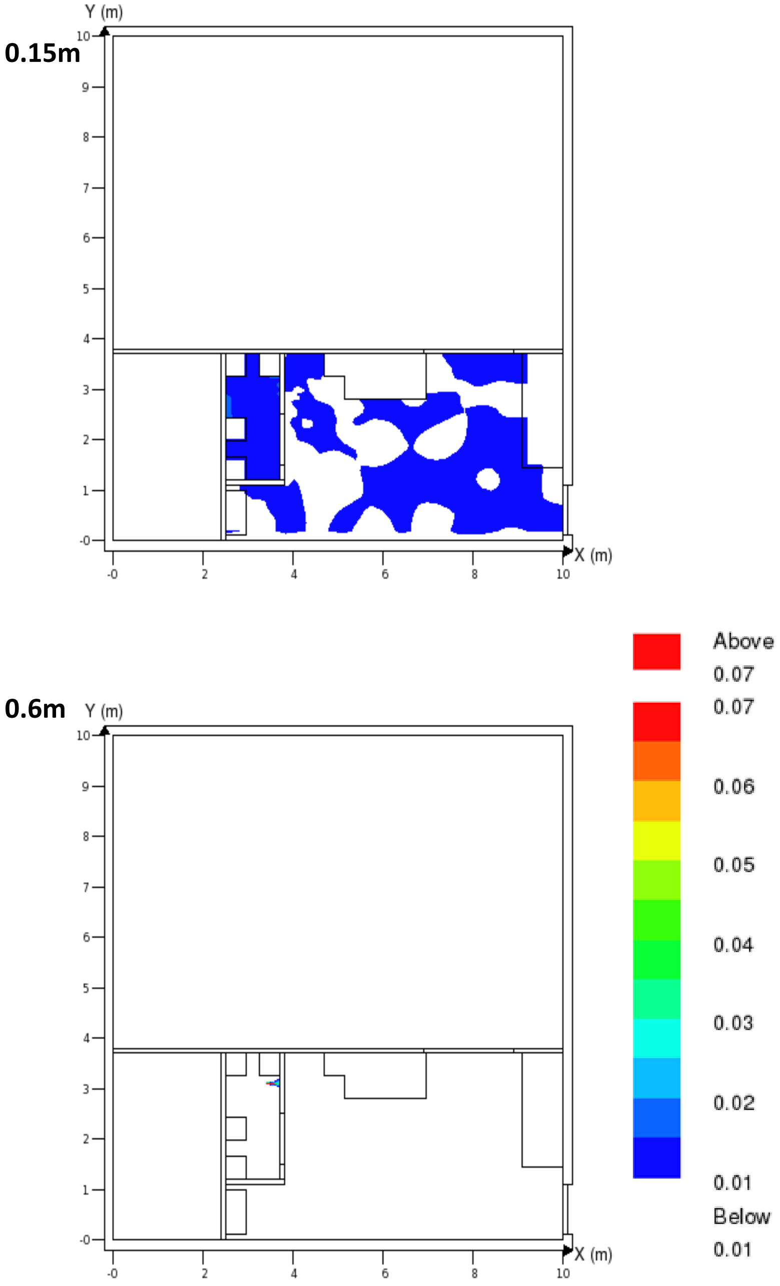
Time elapsed : 1800 s

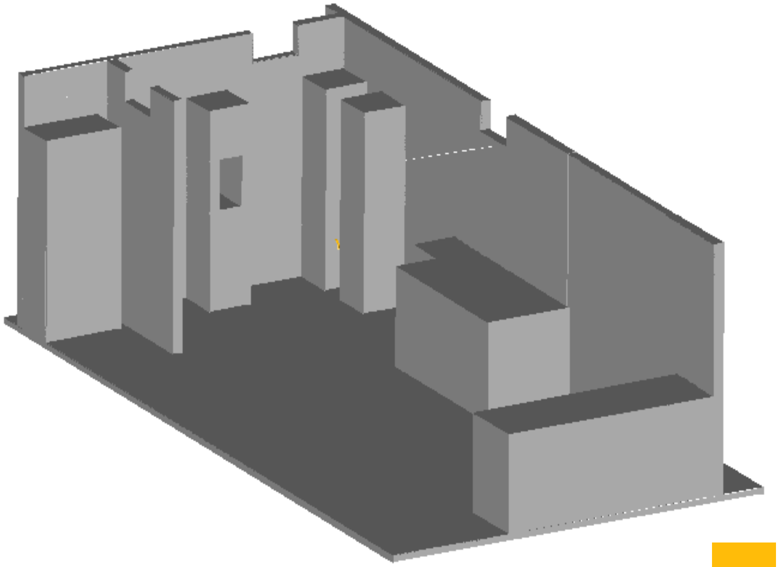
Leak Rate: 0.0015 kg/s

Leak Duration : 2267 s

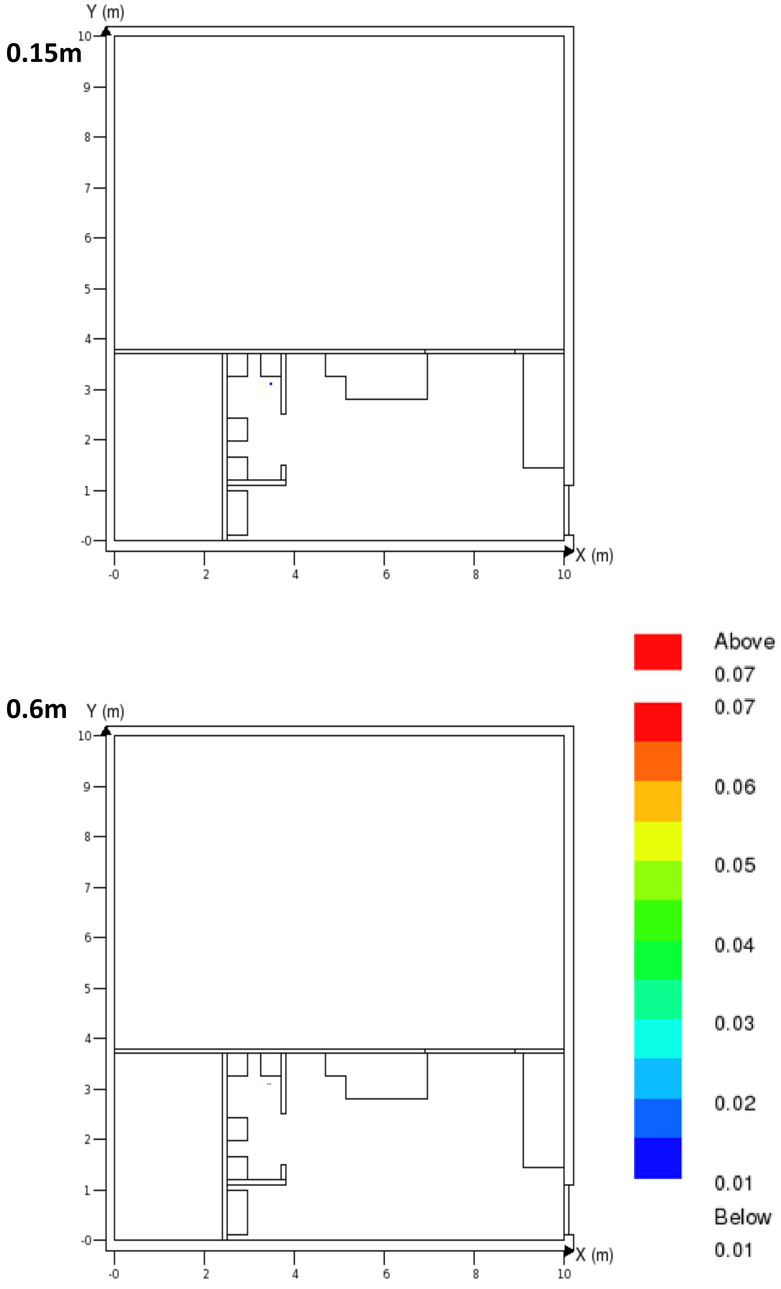


1st floor release : Door Closed
Case # : 212119 (revised 212110)
Species : R-1234ze(E)
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed : 2220 s
Leak Rate: 0.0015 kg/s
Leak Duration : 2219 s

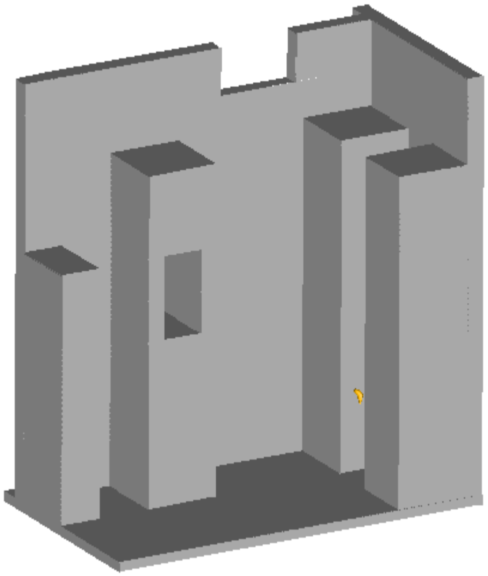




🟧 **≥ 80% LFL**

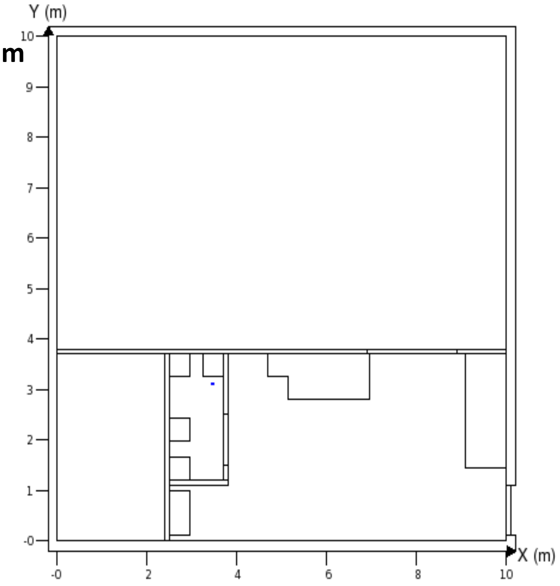


1st floor release : Door open
Case # : 210121
Species : R-1234ze(E)
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed : 20790 s
Leak Rate: 0.00015 kg/s
Leak Duration : 22667 s

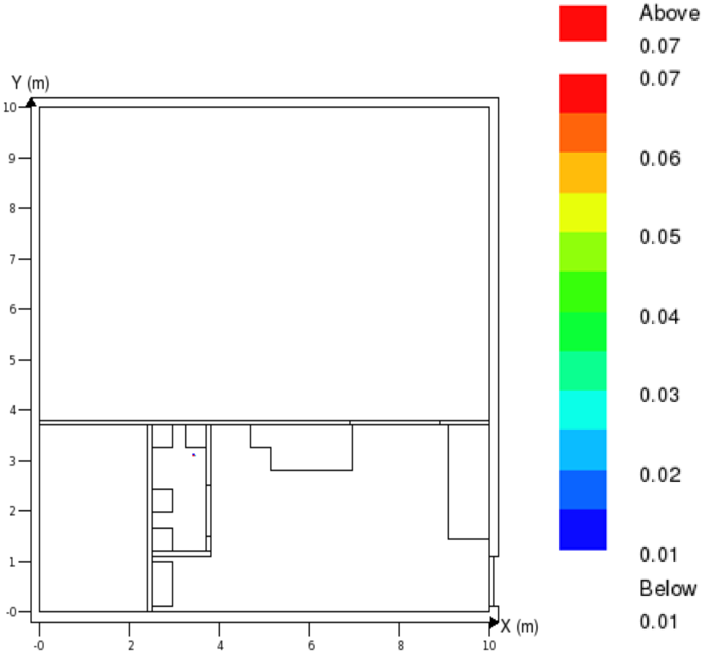


🟧 ≥ 80% LFL

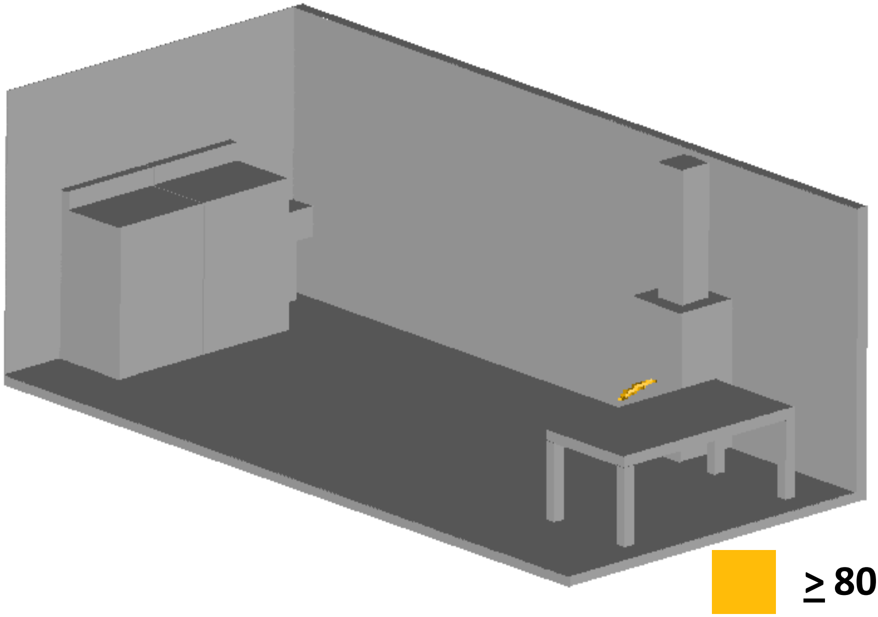
0.15m



0.6m



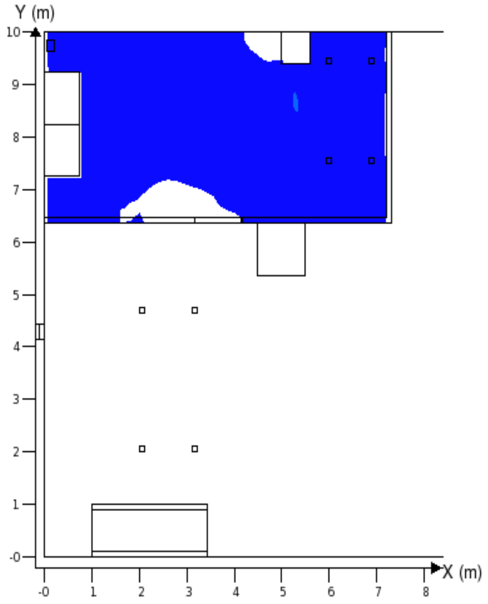
1st floor release : Door Closed
Case # : 212121
Species : R-1234ze(E)
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed : 22650 s
Leak Rate: 0.00015 kg/s
Leak Duration : 22667 s



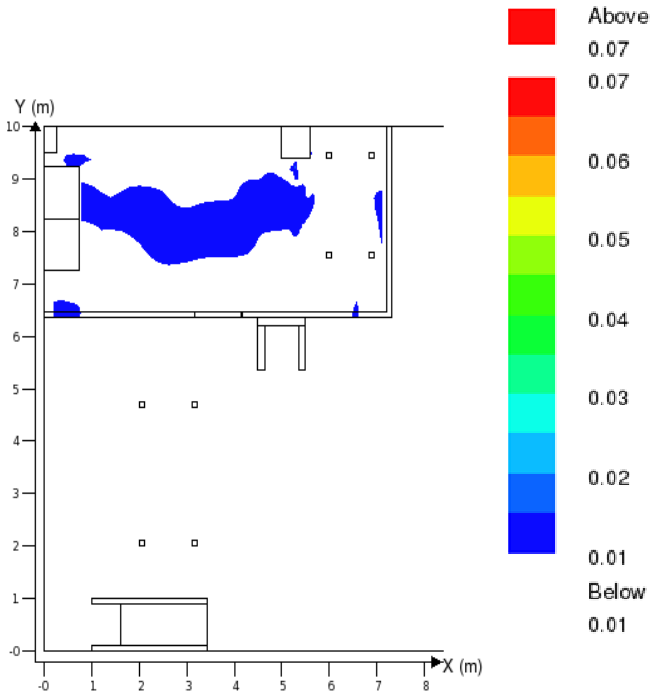
🟧 ≥ 80% LFL

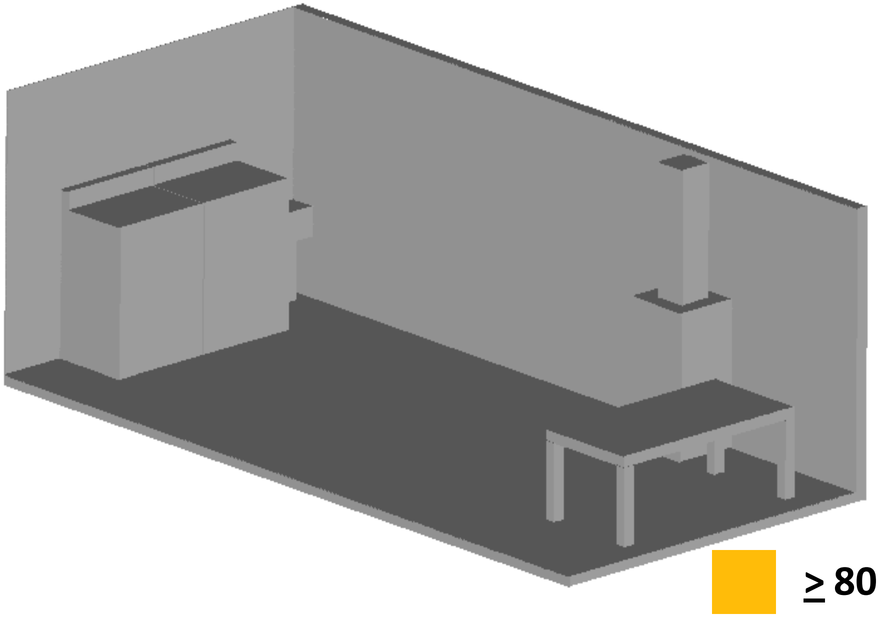
Basement Release
Case # : 210211
Species : R-1234ze(E)
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed : 2070 s
Leak Rate: 0.0015 kg/s
Leak Duration : 2267 s

0.15m



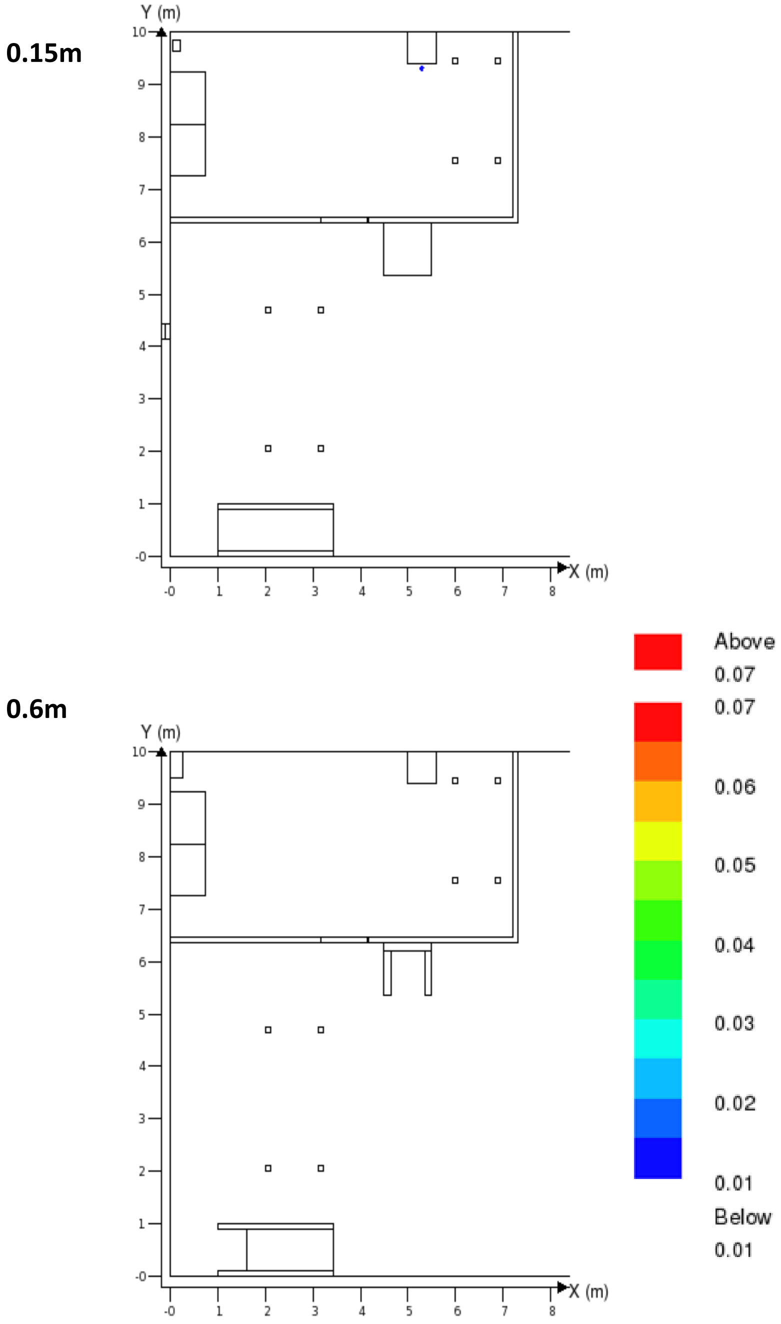
0.6m

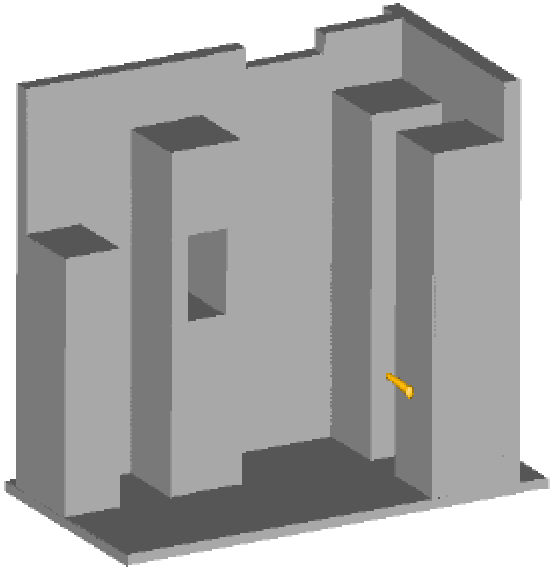




🟧 ≥ 80% LFL

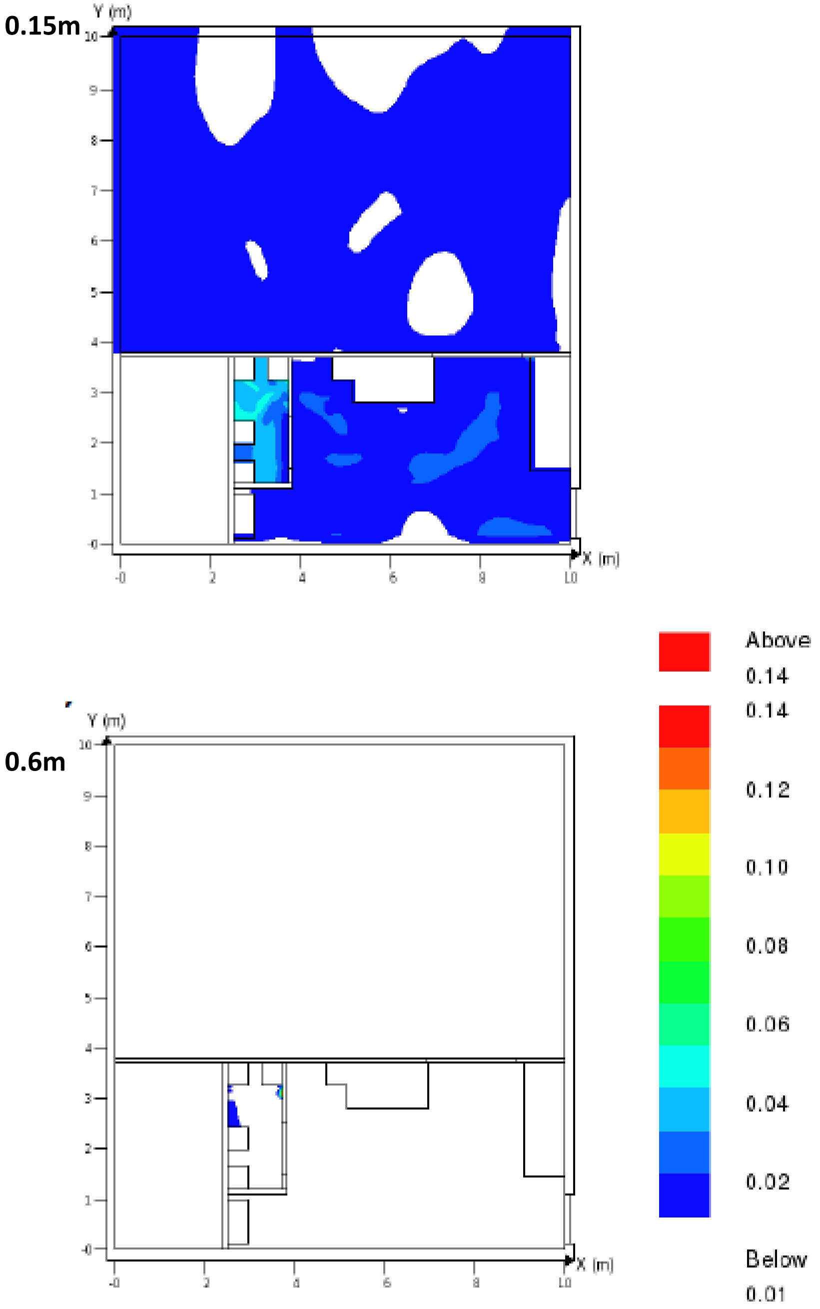
Basement Release
Case # : 210221
Species : R-1234ze(E)
3D Volume plot of 80% LFL
2D Contours between 1% and 7%
Time elapsed : 18360 s
Leak Rate: 0.00015 kg/s
Leak Duration : 22667 s





Job=212110. Var=FMOLE (m3/m3). Time=2249.900 (s).
X=2.3 : 3.65, Y=1.35 : 3.95, Z=-0.03 : 2 m

🟧 **≥ 80% LFL**



1st floor release : Door Closed

Case # : 212110

Species : R-32

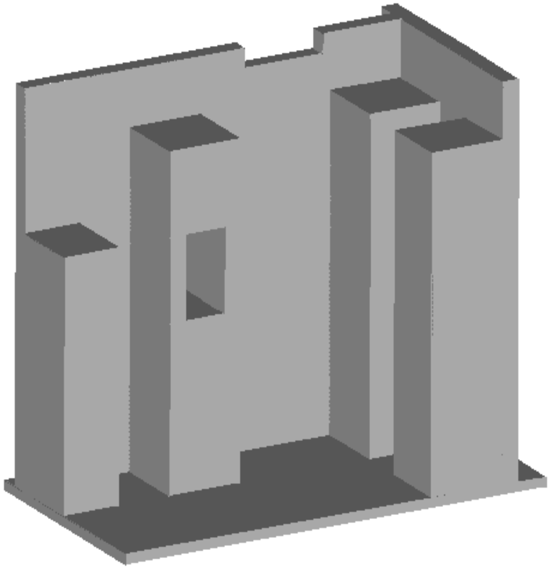
3D Volume plot of 80% LFL

2D Contours between 1% and 14%

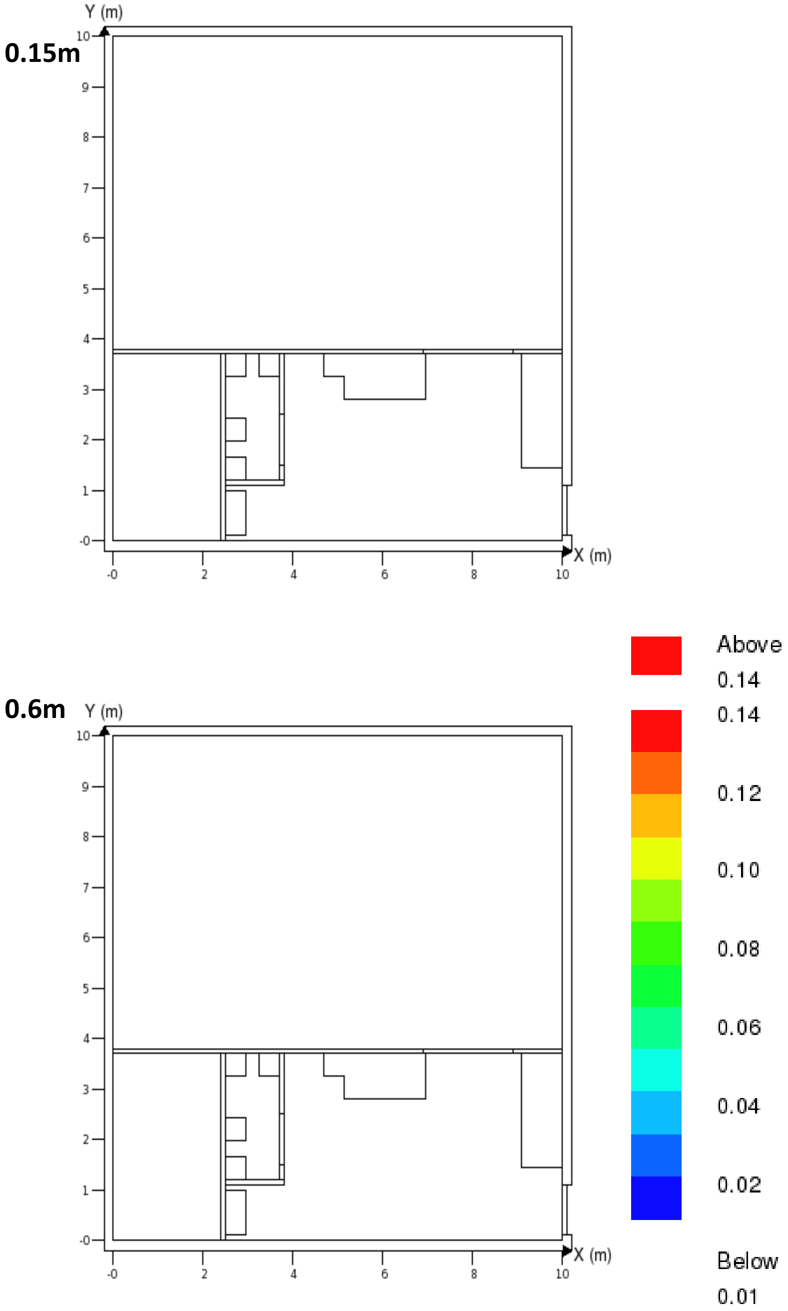
Time elapsed : 2250 s

Leak Rate: 0.0015 kg/s

Leak Duration : 2267 s



🟧 ≥ 80% LFL



1st floor release : Door Closed

Case # : 212110

Species : R-32

3D Volume plot of 80% LFL

2D Contours between 1% and 14%

Time elapsed : 5000 s

Leak Rate: 0.0015 kg/s

Leak Duration : 2267 s

Appendix B

Hughes Associates Inc. Detailed Results

AHRI Refrigerant Concentration Tests

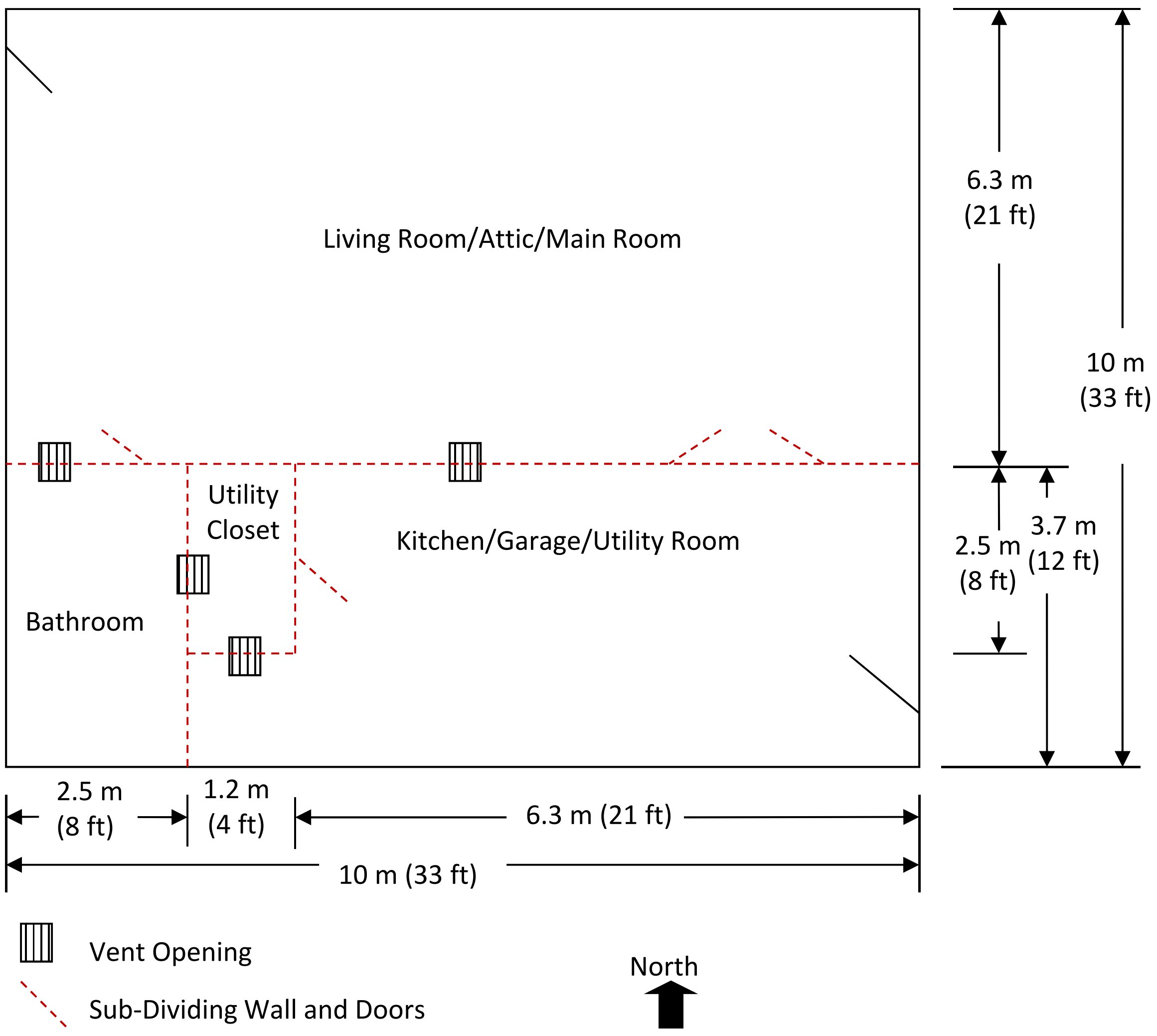
HAI – Baltimore, MD

December 14-18, 2011

Test Parameters

- Two Refrigerants Tested
  - HFO-1234ze (Provided by Honeywell)
  - HFC-32 (Provided by du Pont)
- Four Residential Scenarios
  - Main Floor (Utility Closet)
  - Attic
  - Basement
  - Garage
- Refrigerant Mass
  - 3.4 kg (7.5 lb) for both Refrigerants

Test Enclosure



Enclosure Dimensions - Parameters

	Length		Width		Floor Area		Height		Volume	
Room	[m]	[ft]	[m]	[ft]	[m^2]	[ft^2]	[m]	[ft]	[m^3]	[ft^3]
Living Room Attic Main Room	10.0	33.0	6.3	20.7	63	681	2.4	8	154	5,449
Kitchen*	7.5	24.7	3.7	12.3	25	270	2.4	8	61	2,160
Utility Closet	1.2	4.0	2.5	8.3	3.1	33	2.4	8	8	265
Garage Utility Room	7.5	24.7	3.7	12.3	28	303	2.4	8	69	2,426
Bathroom	2.5	8.3	3.7	12.3	9.5	102	2.4	8	23	815

* Maximum dimensions for Kitchen – Floor Area and Volume Exclude Utility Closet

Test Scenario Parameters

Leakage Scenario		Release Point			Door Settings			HVAC Vents	Leakage Area*		Open Volume**	
			Height									
No.	Name	Room	[m]	[ft]	Kitchen	Utility Closet	Bathroom		$[m^2]$	$[ft^2]$	$[m^3]$	$[ft^3]$
1	Main Floor	Utility Closet	0.6	2	Closed	Open	Closed	Open	0.22	2.4	69	2,426
2	Garage	Garage	0.6	2	Closed	N/A	Closed	Closed	0.17	1.8	69	2,426
3	Basement	Utility Room	0.6	2	Closed-Trimmed	N/A	Open	Closed	0.40	4.3	69	2,426
4	Attic	Attic	0.2	0.5	Closed	Closed	Closed	Closed	0.27	2.9	154	5,449

N/A – Utility Closet removed for Garage and Basement Scenarios

*Leakage area in enclosure boundary as configured for the test scenario (measured with door fan apparatus)

**Open volume does not account for cardboard boxes added to simulate furnishings and clutter

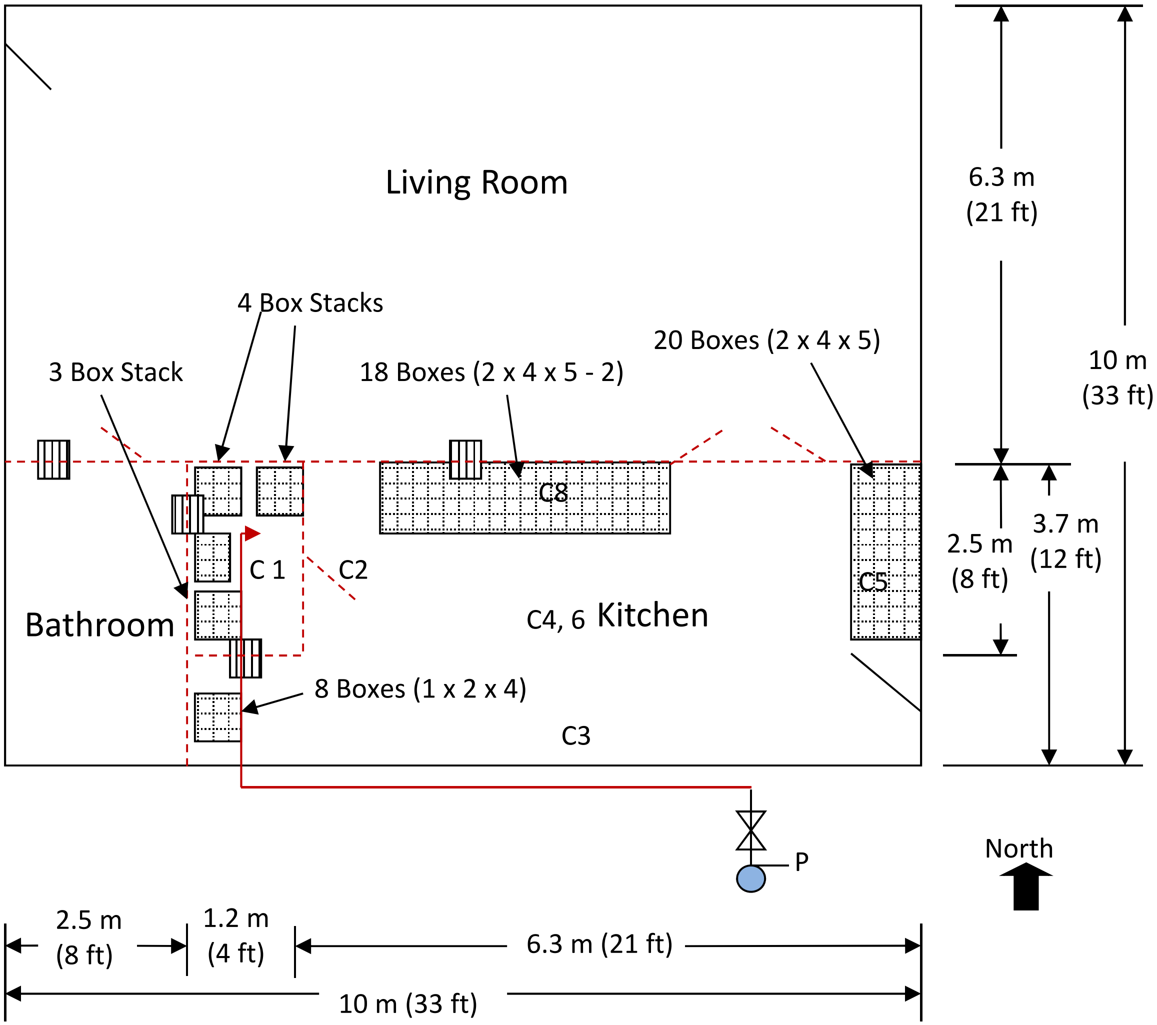
Discharge System

- Agent Cylinder
  - Nominal 12L Cylinder – 13.6 kg (30 lb) Capacity Refrigerant Recovery Cylinder with 6 mm (¼”) SAE Y-Valve (McMaster Carr 17305K72)
  - 6 mm (¼”) Quarter Turn Ball Valve Controlled Flow
  - 9.5 mm (3/8”) Copper Tubing Extended from Cylinder to Release Point – Tubing length varied from 10m (33 ft) to 18m (59 ft)
  - Cylinder Submerged in Warm Water (50 ^{o}C [122 ^{o}F]) to Aid in Discharge
  - Cylinder Pressure Targets for Discharge
    - HFO-1234ze – 7.6 bar, gauge (110 psig)
    - HFC-32 – 26.5 bar, gauge (385 psig)

Instrumentation

- Cylinder Pressure
  - HFO-1234ze – Pressure Transducer with 0-20.7 bar, gauge (0-300 psig) range – Omega Model PX603-300G5V
  - HFC-32 – Pressure Transducer with 0-68.9 bar, gauge (0-1000 psig) range – Omega Model PX603-1KG5V
- Refrigerant Concentration
  - Tripoint Instruments Model 123
    - 3 Measurement Points
    - Sample Flow Rate: 1.5 LPM
  - Henze Houck Processmesstechnik/Analytik GMBH Sensors (Provided by Honeywell)
    - 5 Measurement Points
    - Sample Flow Rate: 0.9 LPM
  - 6 mm (1/4”) polyethylene tubing running from analyzers to sampling points – 30.5 m (100 ft) in length – Tubing was not cut to maintain consistent transport delays between sampling points and between tests

Main Floor Scenario Schematic



▥ Vent Opening

● Discharge Cylinder

⧖

— Discharge Piping (8 mm (3/8") Copper Tubing)

P Pressure Measurement

▦ Cardboard Boxes – 0.45 m (1.5 ft) Cube

Concentration Measurement:
1-Utility Closet 0.15m (0.5 ft) above Floor
2-Outside Utility Closet 0.15m (0.5 ft) above Floor
3-Side of Kitchen 0.4m (1.4 ft) above Floor
4-Mid-Kitchen 0.15m (0.5 ft) above Floor
5-Side of Kitchen 0.9m (3 ft) above Floor
6-Mid-Kitchen 1.5m (5 ft) above Floor
8-Side of Kitchen 0.8m (2.7 ft) above Floor

Main Floor Scenario Photographs

Inside Kitchen
– Facing West

Inside Utility Closet –
Facing North

Inside Kitchen
– Facing East

Main Floor Scenario Release and Sampling Point Coordinates

Point	Description	West (X)		North (Y)		Elevation (Z)	
		[m]	[ft]	[m]	[ft]	[m]	[ft]
	Release Point	6.6	21.7	3.1	10.3	0.6	2.0
1	Inside Utility Closet	6.6	21.5	2.6	8.5	0.2	0.5
2	Outside Utility Closet	5.7	18.8	2.6	8.5	0.2	0.5
3	South Wall	3.8	12.5	0.0	0.0	0.4	1.4
4	Center Kitchen Low	3.0	10.0	1.9	6.2	0.2	0.5
5	East Wall Counter Top	0.0	0.0	1.9	6.3	0.9	3.0
6	Mid Kitchen High	3.0	10.0	1.9	6.2	1.5	5.0
8	Kitchen Wall - Counter Top	4.3	14.0	3.7	12.0	0.9	3.0

Main Floor Scenario Refrigerant Release Summary

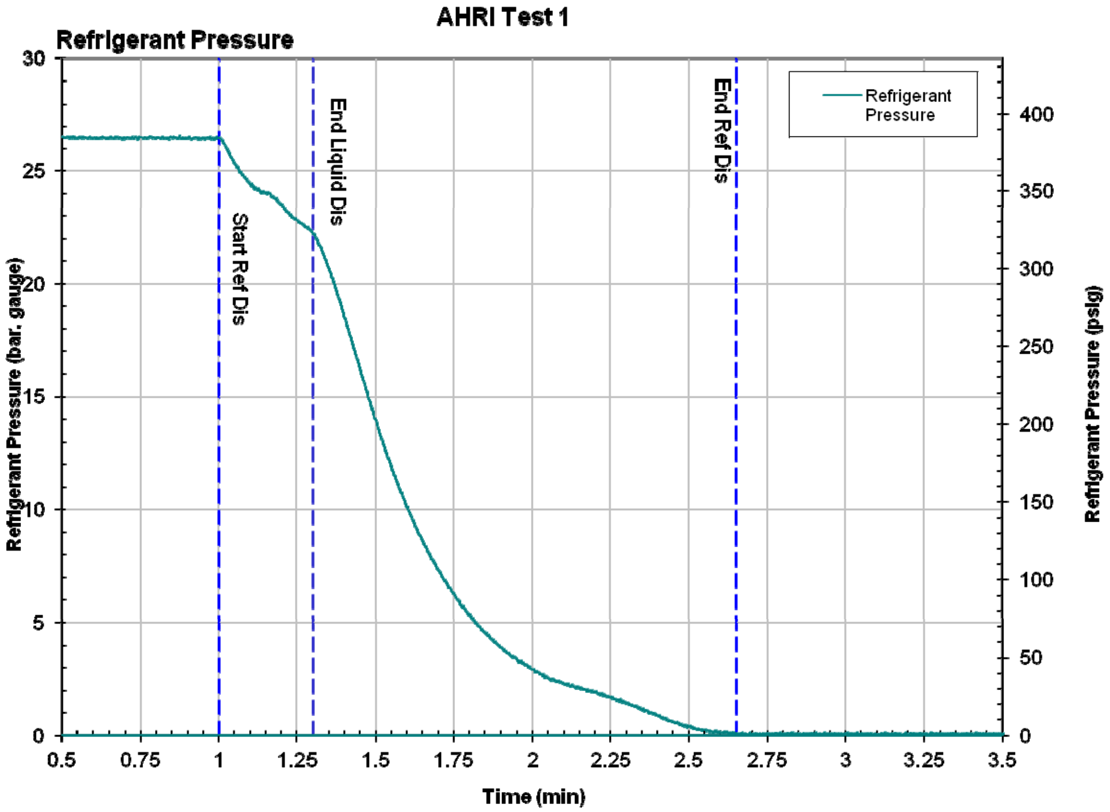
Test	Refrigerant	Refrig. Discharge Time		Refrigerant Pressures				Refrigerant Flow Rate (Liquid)*	
		Liquid	Total	Maximum		Ave Over Discharge (Total)			
		[sec]	[sec]	[bar]	[psig]	[bar]	[psig]	[g/s]	[lb/s]
AHRI Test 1	HFC-32	18.0	99.0	26.6	386	9.3	134	170	0.38
AHRI Test 2	HFO-1234ze	39.0	84.0	7.4	108	4.1	59	78	0.17

*Refrigerant flow rate based on 90% of mass delivered during liquid discharge

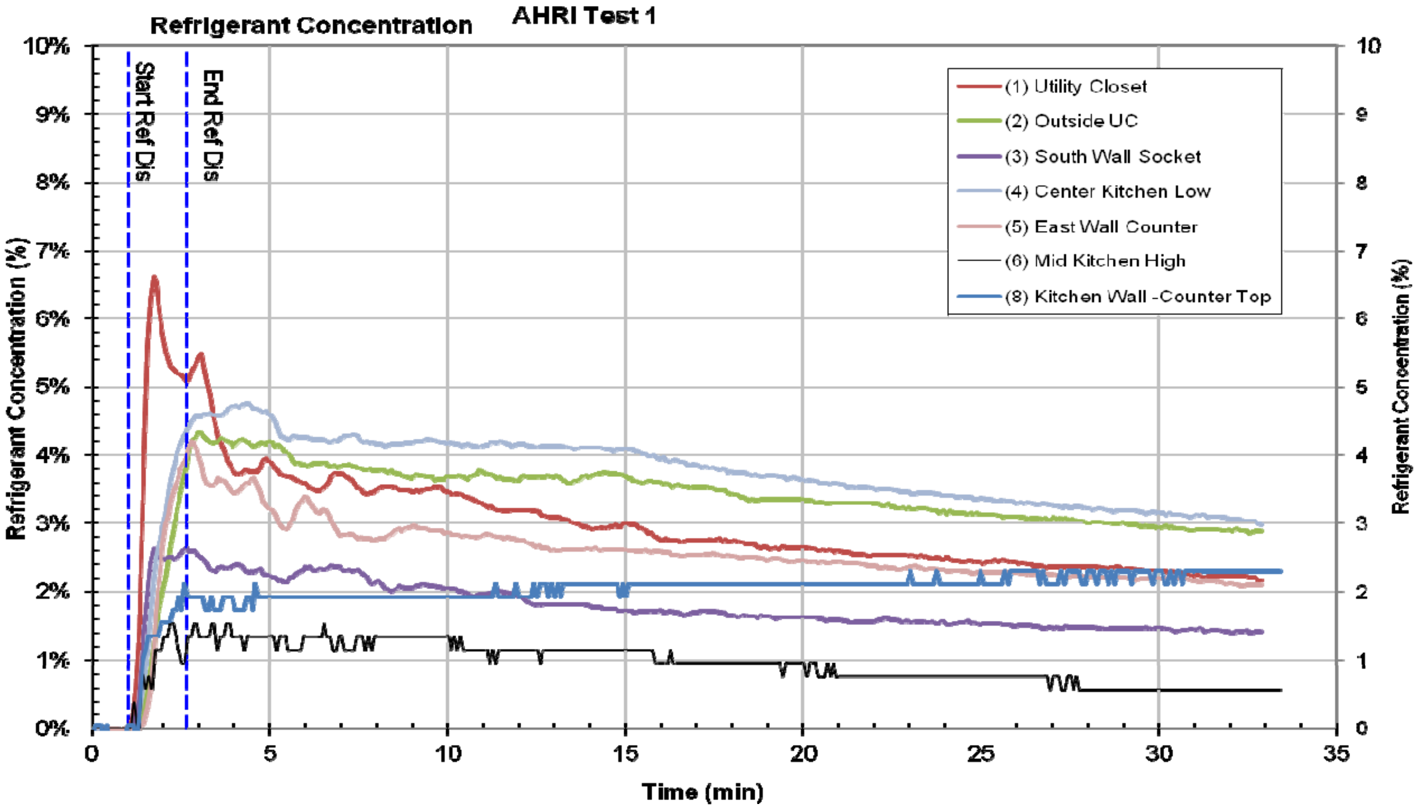
Main Floor Scenario Concentration

Sampling Point			HFC-32	HFO-1234ze
(1) Utility Closet	Maximum	[%]	6.61	3.57
	5 min Average	[%]	4.18	2.42
	30 min Average	[%]	3.05	2.07
(2) Outside UC	Maximum	[%]	4.33	2.98
	5 min Average	[%]	3.27	2.17
	30 min Average	[%]	3.39	2.23
(3) South Wall Socket	Maximum	[%]	2.65	1.57
	5 min Average	[%]	2.16	1.25
	30 min Average	[%]	1.81	1.01
(4) Center Kitchen Low	Maximum	[%]	4.76	2.96
	5 min Average	[%]	3.74	2.40
	30 min Average	[%]	3.74	2.35
(5) East Wall Counter	Maximum	[%]	4.20	2.50
	5 min Average	[%]	2.90	1.75
	30 min Average	[%]	2.59	1.10
(6) Mid Kitchen High	Maximum	[%]	1.54	0.25
	5 min Average	[%]	1.18	0.05
	30 min Average	[%]	0.99	0.01
(8) Kitchen Wall -Counter Top	Maximum	[%]	2.30	1.35
	5 min Average	[%]	1.66	1.02
	30 min Average	[%]	2.02	0.85

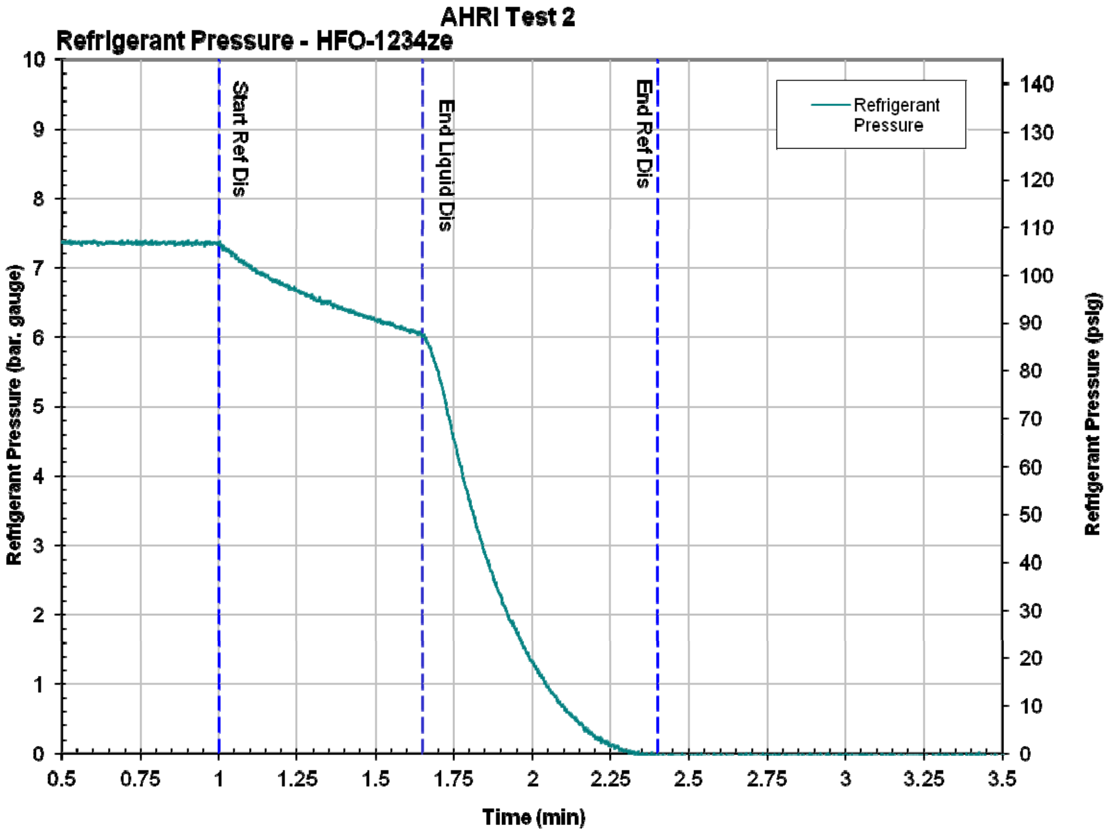
HFC-32 Cylinder Pressure during Main Floor Scenario Test



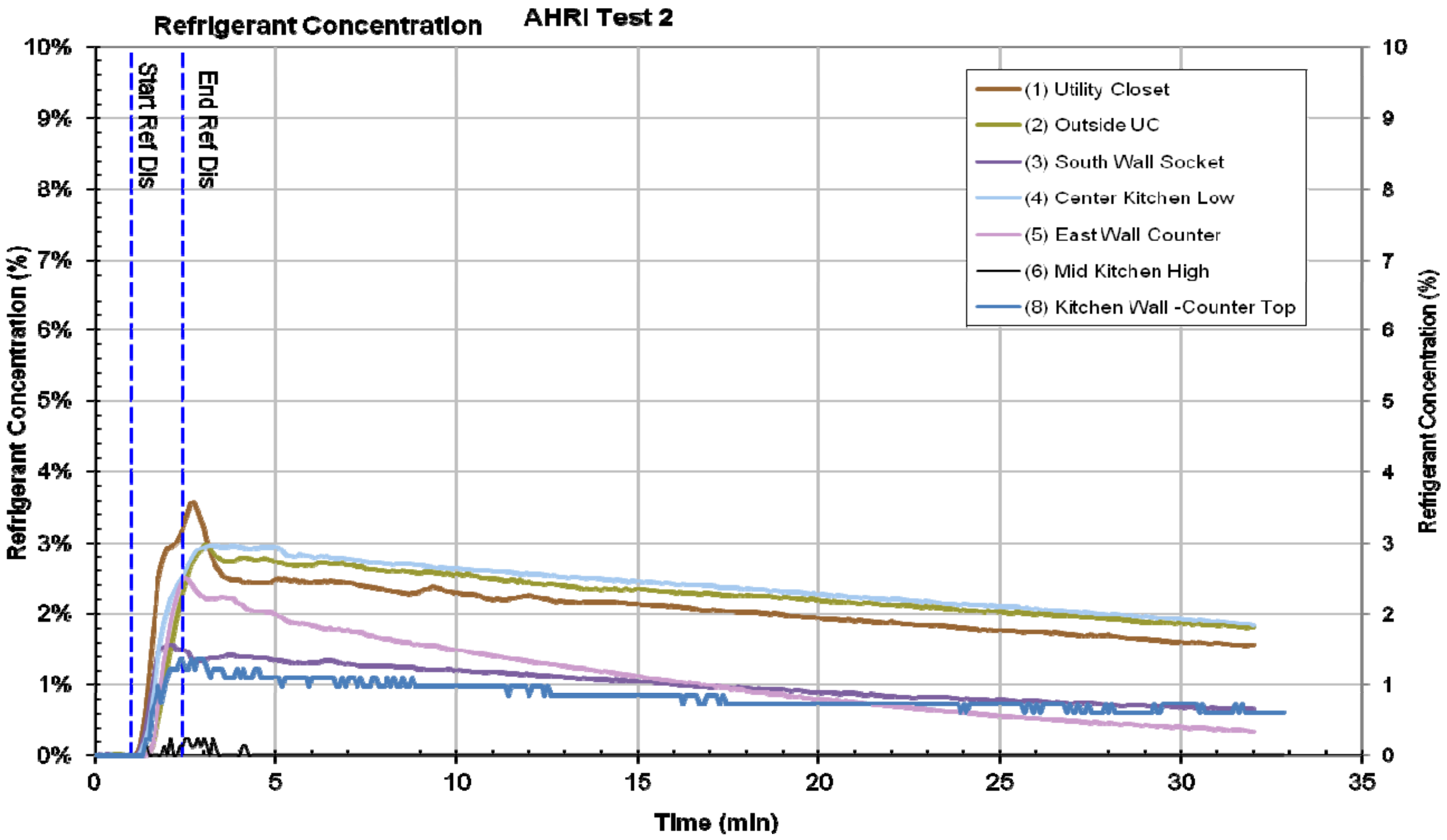
HFC-32 Concentrations during Main Floor Scenario Test



HFO-1234ze Cylinder Pressure during Main Floor Scenario Test



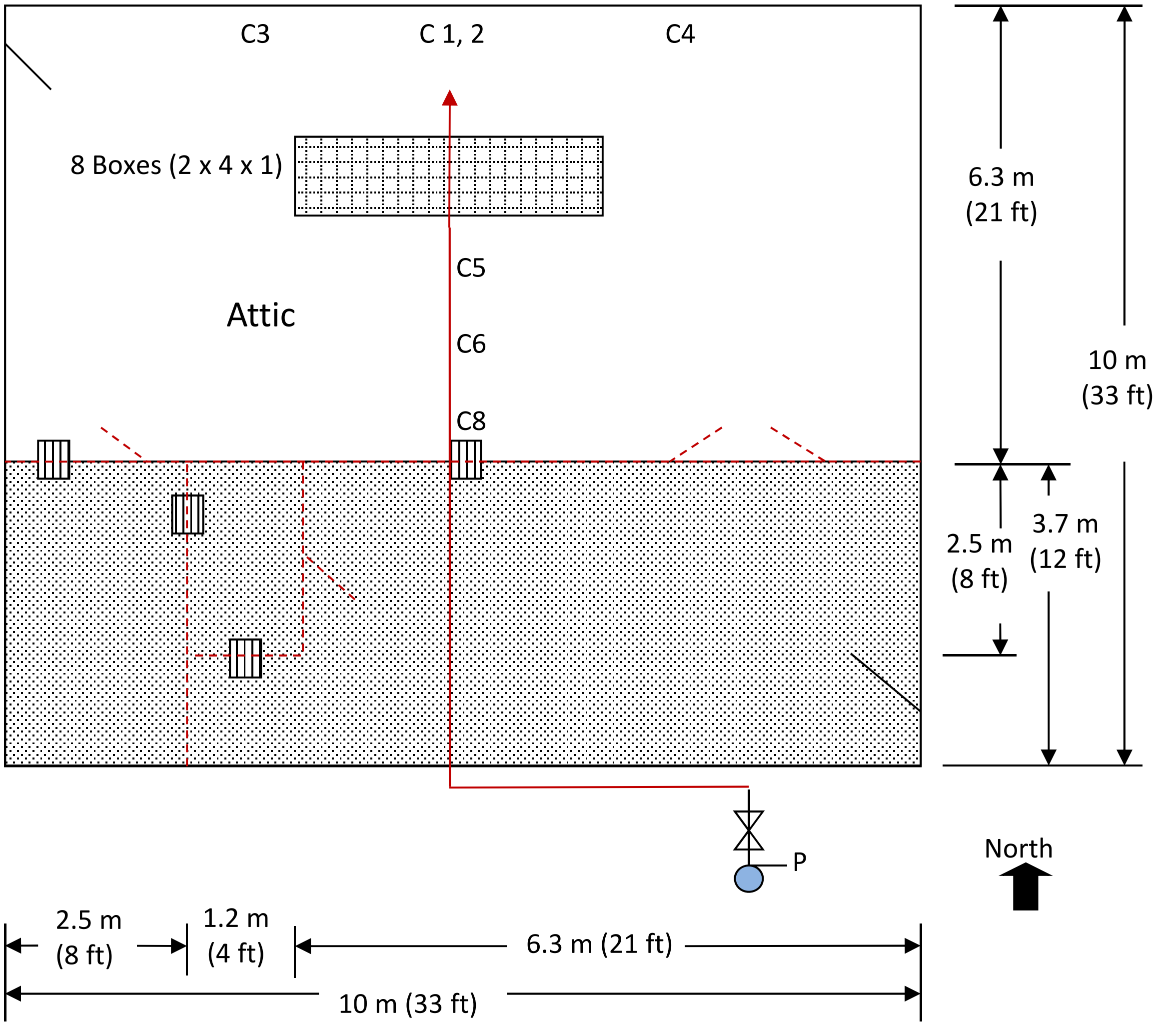
HFO-1234ze Concentrations during Main Floor Scenario Test



Main Floor Scenario Summary

- Similar Concentration Profiles for both refrigerants
  - Highest in the utility closet itself (1), concentrations then follow a flow path across the room (2 and 4) towards the opposite wall (5). Relatively less lateral dispersion (3 and 8) and the refrigerant remains near the floor (6, the mid kitchen at 1.5 m (5 ft) is either lowest or below detection)
- HFO-1234ze had lower concentrations reflecting higher vapor density
- HFC-32 had quicker discharge
  - liquid discharge time of 18 sec compared to 39 sec for HFO-1234ze
- HFO-1234ze had greater tendency to remain at floor level (lower density and quicker discharge contributed to this)
  - HFC-32 had concentration well above detection limit mid-kitchen high point (6) while HFO-1234ze barely exceeded this level
- HFC-32 concentrations below lower flammability limit of 14% at all monitored points
  - maximum of 6.6 % low in utility closet

Attic Scenario Schematic



▥ Vent Opening

⋰ Sub-Dividing Wall and Doors

● Discharge Cylinder

⧖ Discharge Valve

— Discharge Piping (8 mm (3/8”) Copper Tubing)

P Pressure Measurement

▦ Cardboard Boxes – 0.45 m (1.5 ft) Cube

Concentration Measurement:
1-In Front of Leak Low 0.15m (0.5 ft) above Floor
2-In Front of Leak High 0.6m (2 ft) above Floor
3-In Front of Leak West 0.15m (0.5 ft) above Floor
4-In Front of Leak East 0.15m (0.5 ft) above Floor
5-Behind Leak [2 m (6.5 ft)]- 0.15m (0.5 ft) above Floor
6-Behind Leak [3.2m (6.5 ft)]-0.15m (0.5 ft) above Floor
8-South Wall – Behind Leak

Attic Scenario Photographs

Inside Garage Facing East

Inside Garage Facing West

Attic Scenario Release and Sampling Point Coordinates

Point	Description	West (X)		North (Y)		Elevation (Z)	
		[m]	[ft]	[m]	[ft]	[m]	[ft]
	Release Point	5.0	16.5	4.6	15.0	0.2	0.5
1	In Front of Leak - Low	5.0	16.5	5.6	18.5	0.2	0.5
2	In Front of Leak - High	5.0	16.5	5.6	18.5	0.6	2.0
3	In Front of Leak - West	6.9	22.5	5.6	18.5	0.2	0.5
4	In Front of Leak - East	3.2	10.5	5.6	18.5	0.2	0.5
5	Behind Leak [2m (6.5 ft)]	5.0	16.5	2.6	8.5	0.2	0.5
6	Behind Leak [3.2m (10.5 ft)]	5.0	16.5	1.4	4.5	0.2	0.5
8	South Wall - Behind Leak	5.0	16.5	0.0	0.0	0.2	0.5

Attic Scenario Refrigerant Release Rate Summary

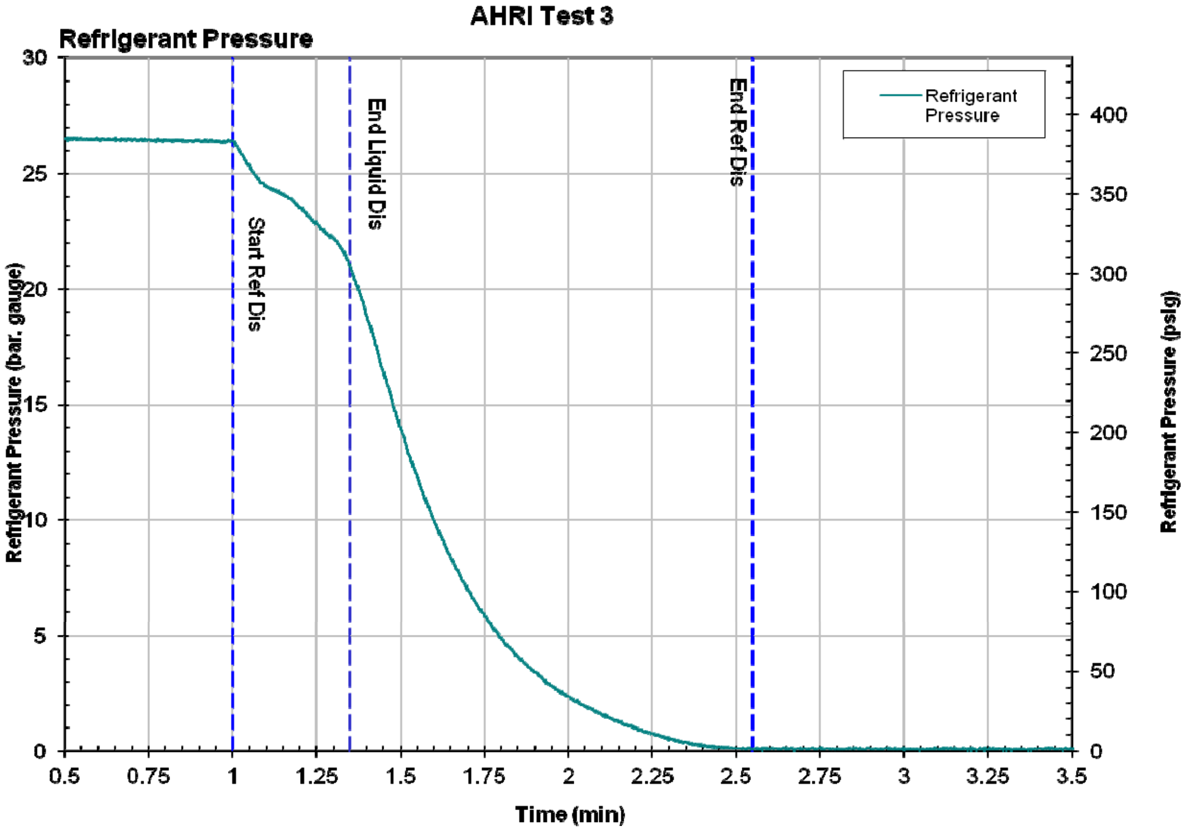
Test	Refrigerant	Refrig. Discharge Time		Refrigerant Pressures				Refrigerant Flow Rate (Liquid)*	
		Liquid	Total	Maximum		Ave Over Discharge (Total)			
		[sec]	[sec]	[bar]	[psig]	[bar]	[psig]	[g/s]	[lb/s]
AHRI Test 3	HFC-32	21.0	93.0	26.7	387	9.6	139	146	0.32
AHRI Test 4	HFO-1234ze	31.8	84	8.1	118	4.2	61	96	0.21

*Refrigerant flow rate based on 90% of mass delivered during liquid discharge

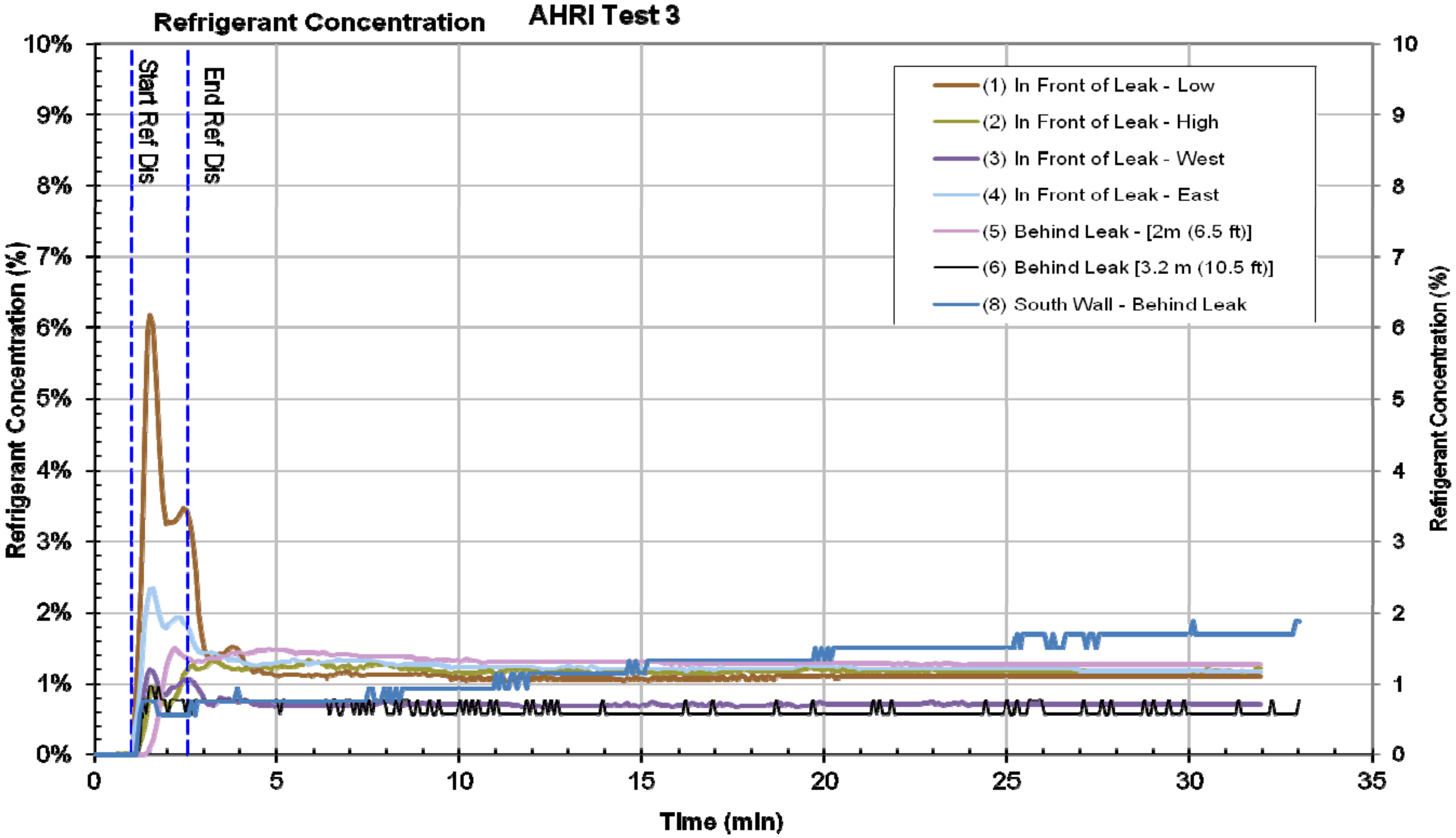
Attic Scenario Concentration Summary

Sampling Point			HFC-32	HFO-1234ze
(1) In Front of Leak - Low	Maximum	[%]	6.17	3.61
	5 min Average	[%]	2.06	1.26
	30 min Average	[%]	1.25	0.79
(2) In Front of Leak - High	Maximum	[%]	1.34	0.80
	5 min Average	[%]	1.05	0.60
	30 min Average	[%]	1.16	0.71
(3) In Front of Leak - West	Maximum	[%]	1.19	0.62
	5 min Average	[%]	0.77	0.46
	30 min Average	[%]	0.72	0.43
(4) In Front of Leak - East	Maximum	[%]	2.34	1.28
	5 min Average	[%]	1.44	0.89
	30 min Average	[%]	1.26	0.82
(5) Behind Leak - [6.5 ft]	Maximum	[%]	1.51	1.02
	5 min Average	[%]	1.18	0.77
	30 min Average	[%]	1.28	0.87
(6) Behind Leak [10.5 ft]	Maximum	[%]	0.96	0.62
	5 min Average	[%]	0.72	0.50
	30 min Average	[%]	0.63	0.50
(8) South Wall - Behind Leak	Maximum	[%]	1.89	1.10
	5 min Average	[%]	0.68	0.80
	30 min Average	[%]	1.21	0.92

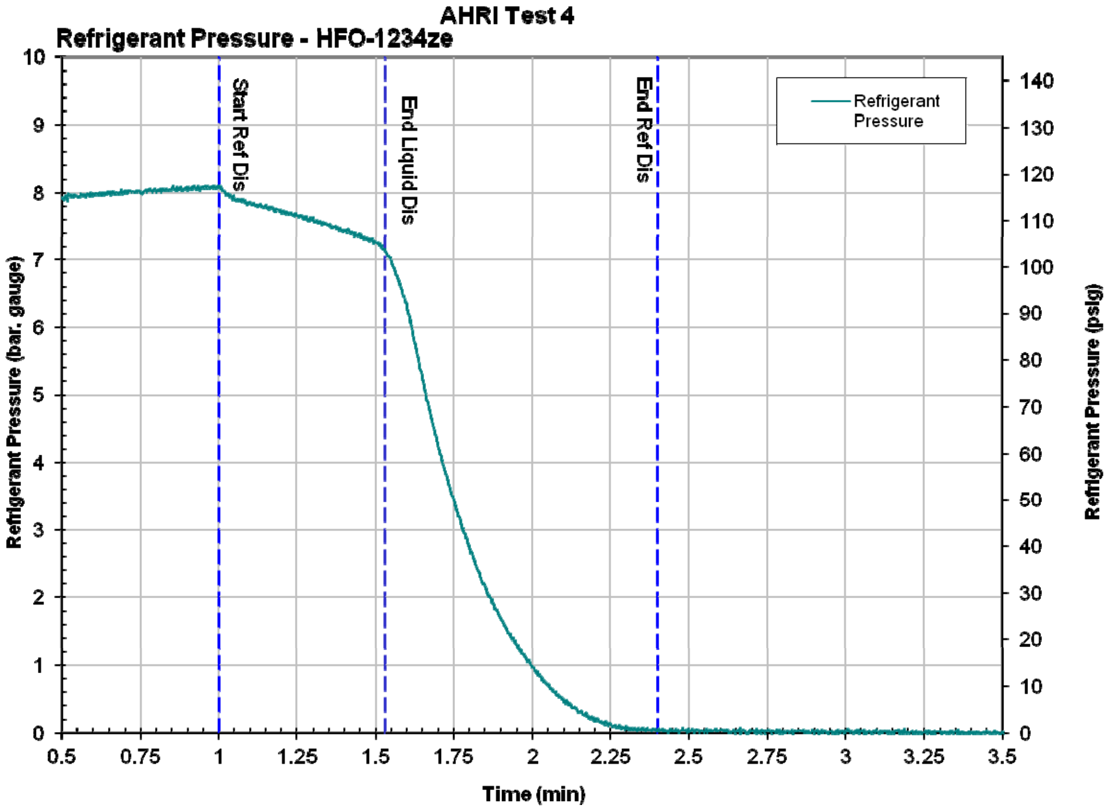
HFC-32 Cylinder Pressures During Attic Scenario Test



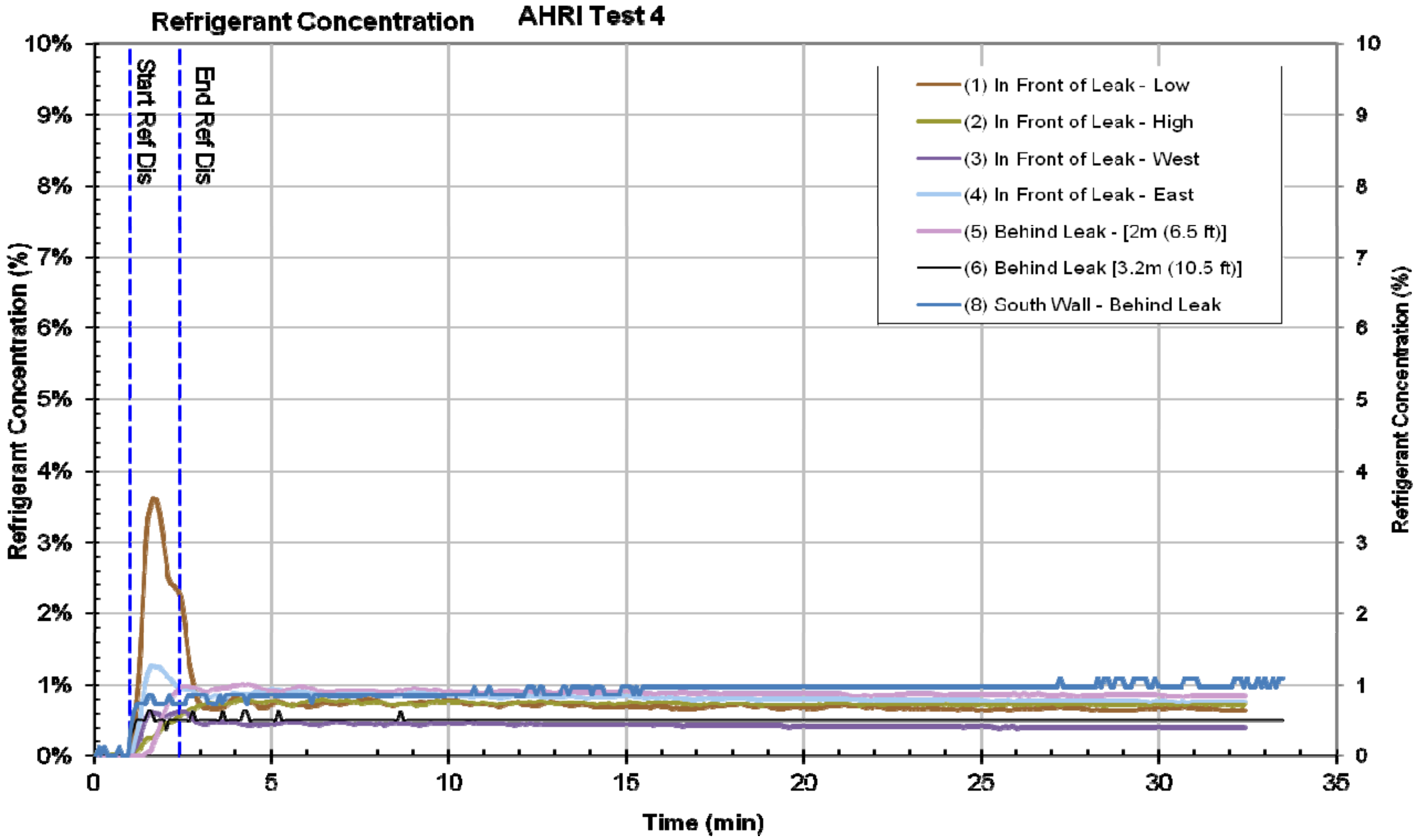
HFC-32 Concentrations During Attic Scenario Test



HFO-1234ze Cylinder Pressures During Attic Scenario Test



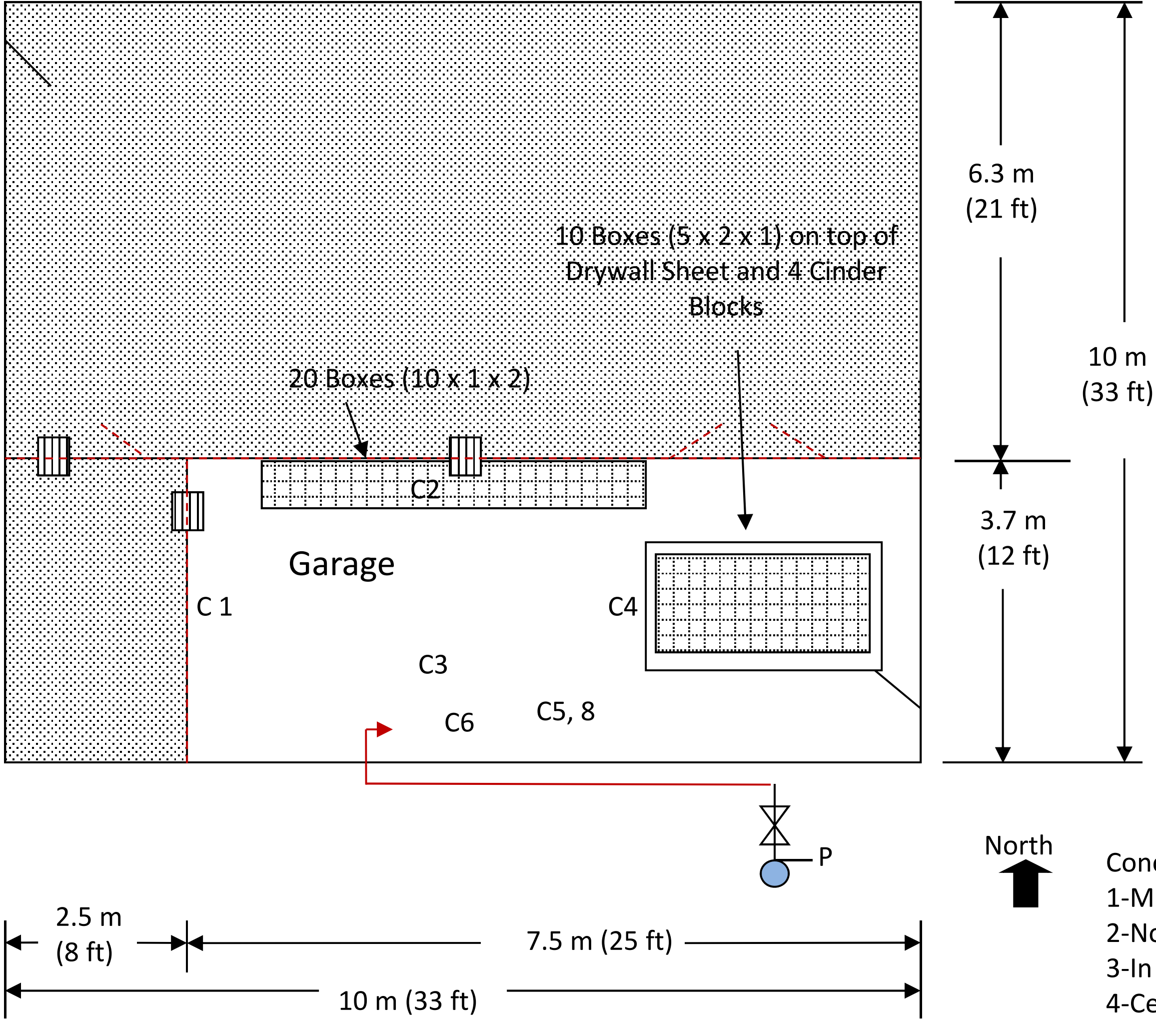
HFO-1234ze Concentrations During Attic Scenario Test



Attic Scenario Results

- Similar Concentration Profiles for both refrigerants
  - Highest in front of leak and quickly becoming well mixed.
- HFO-1234ze had lower concentrations reflecting higher vapor density
- HFC-32 had quicker discharge
  - liquid discharge time of 21 sec compared to 31.8 sec for HFO-1234ze
- HFC-32 concentrations well below lower flammability limit of 14% at all monitored points
  - maximum of 6.2 % in front of leak

Garage Scenario Schematic



▥ Vent Opening

⋱ Sub-Dividing Wall and Doors

● Discharge Cylinder

⧗ Discharge Valve

— Discharge Piping (8 mm (3/8") Copper Tubing)

P Pressure Measurement

⊞ Cardboard Boxes – 0.45 m (1.5 ft) Cube

North ⬆

Concentration Measurements:
1-Mid West Wall - 0.8m (2.7 ft) above Floor
2-North Wall – Counter Top 1m (3.3 ft) above Floor
3-In Front of Leak – North - 0.15m (0.5 ft) above Floor
4-Center Room – Low - 0.05m (0.2 ft) above Floor
5-In Front of Leak [2.3m (7.5 ft)]-0.15m (0.5 ft) above Floor
6-In Front of Leak [0.6m (2 ft)]- 0.15m (0.5 ft) above Floor
8-In Front of Leak – High-1.5m (5 ft) above Floor

Garage Scenario Photographs

Facing West

Facing East

Facing East

Garage Scenario Release and Sampling Point Coordinates

Point	Description	West (X)		North (Y)		Elevation (Z)	
		[m]	[ft]	[m]	[ft]	[m]	[ft]
	Release Point	5.7	18.7	0.5	1.5	0.6	2.0
1	Mid West Wall - Mid Ht	7.5	24.7	2.1	7.0	0.8	2.7
2	North Wall - Counter Top	5.1	16.7	3.7	12.0	1.0	3.3
3	In Front of Leak - North	5.4	17.7	1.2	4.0	0.2	0.5
4	Center Room - Low	2.7	9.0	1.8	6.0	0.1	0.2
5	In Front of Leak [2.3m (7.5 ft)]	3.4	11.2	0.6	2.0	0.2	0.5
6	In Front of Leak [0.6m (2 ft)]	5.1	16.7	0.5	1.5	0.2	0.5
8	In Front of Leak - High	3.4	11.2	0.6	2.0	1.5	5.0

Garage Scenario Refrigerant Release Summary

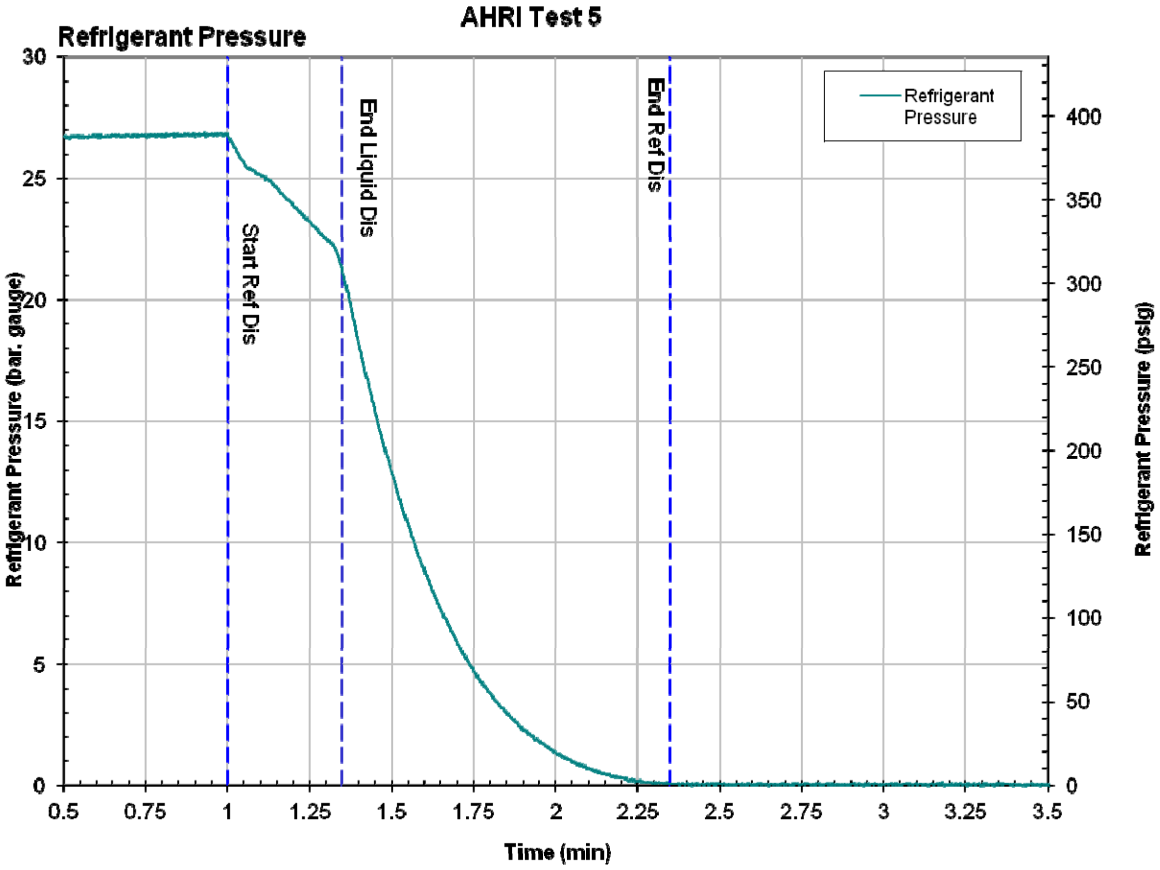
Test	Refrigerant	Refrig. Discharge Time		Refrigerant Pressures				Refrigerant Flow Rate (Liquid)*	
		Liquid	Total	Maximum		Ave Over Discharge (Total)			
		[sec]	[sec]	[bar]	[psig]	[bar]	[psig]	[g/s]	[lb/s]
AHRI Test 5	HFC-32	21.0	81.0	26.9	390	10.4	151	146	0.32
AHRI Test 6	HFO-1234ze	31.8	81	8.1	118	4.2	61	96	0.21

*Refrigerant flow rate based on 90% of mass delivered during liquid discharge

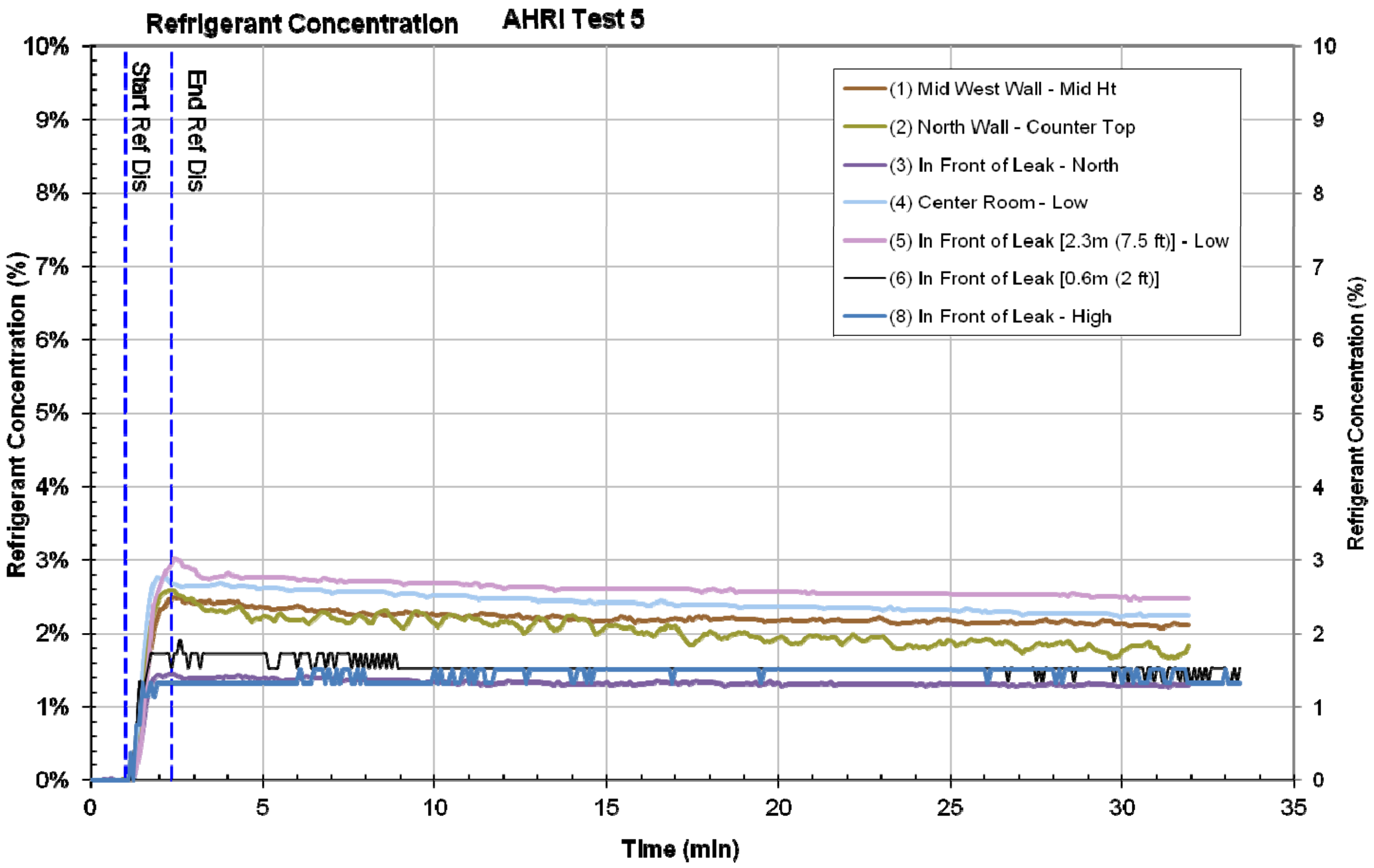
Garage Scenario Concentration Measurement Summary

Sampling Point			HFC-32	HFO-1234ze
(1) In Front of Leak - Low	Maximum	[%]	2.49	1.21
	5 min Average	[%]	2.08	0.96
	30 min Average	[%]	2.18	1.05
(2) North Wall - Counter Top	Maximum	[%]	2.59	1.19
	5 min Average	[%]	2.07	0.94
	30 min Average	[%]	2.01	1.01
(3) In Front of Leak - North	Maximum	[%]	1.44	0.72
	5 min Average	[%]	1.24	0.60
	30 min Average	[%]	1.31	0.63
(4) Center Room - Low	Maximum	[%]	2.77	1.42
	5 min Average	[%]	2.36	1.18
	30 min Average	[%]	2.39	1.22
(5) In Front of Leak [2.3m (7.5 ft)] - Low	Maximum	[%]	3.02	1.45
	5 min Average	[%]	2.41	1.17
	30 min Average	[%]	2.56	1.26
(6) In Front of Leak [0.6m (2 ft)]	Maximum	[%]	1.92	1.11
	5 min Average	[%]	1.57	0.94
	30 min Average	[%]	1.55	0.91
(8) In Front of Leak - High	Maximum	[%]	1.51	1.22
	5 min Average	[%]	1.22	0.91
	30 min Average	[%]	1.43	1.09

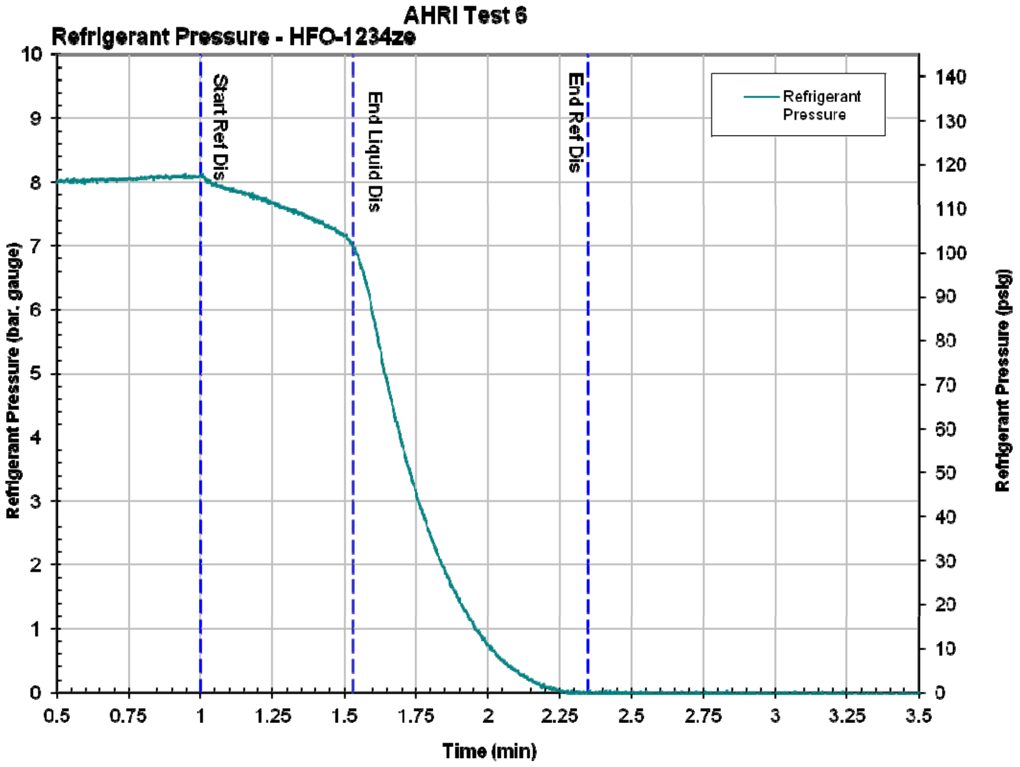
HFC-32 Cylinder Pressures During Garage Scenario Test



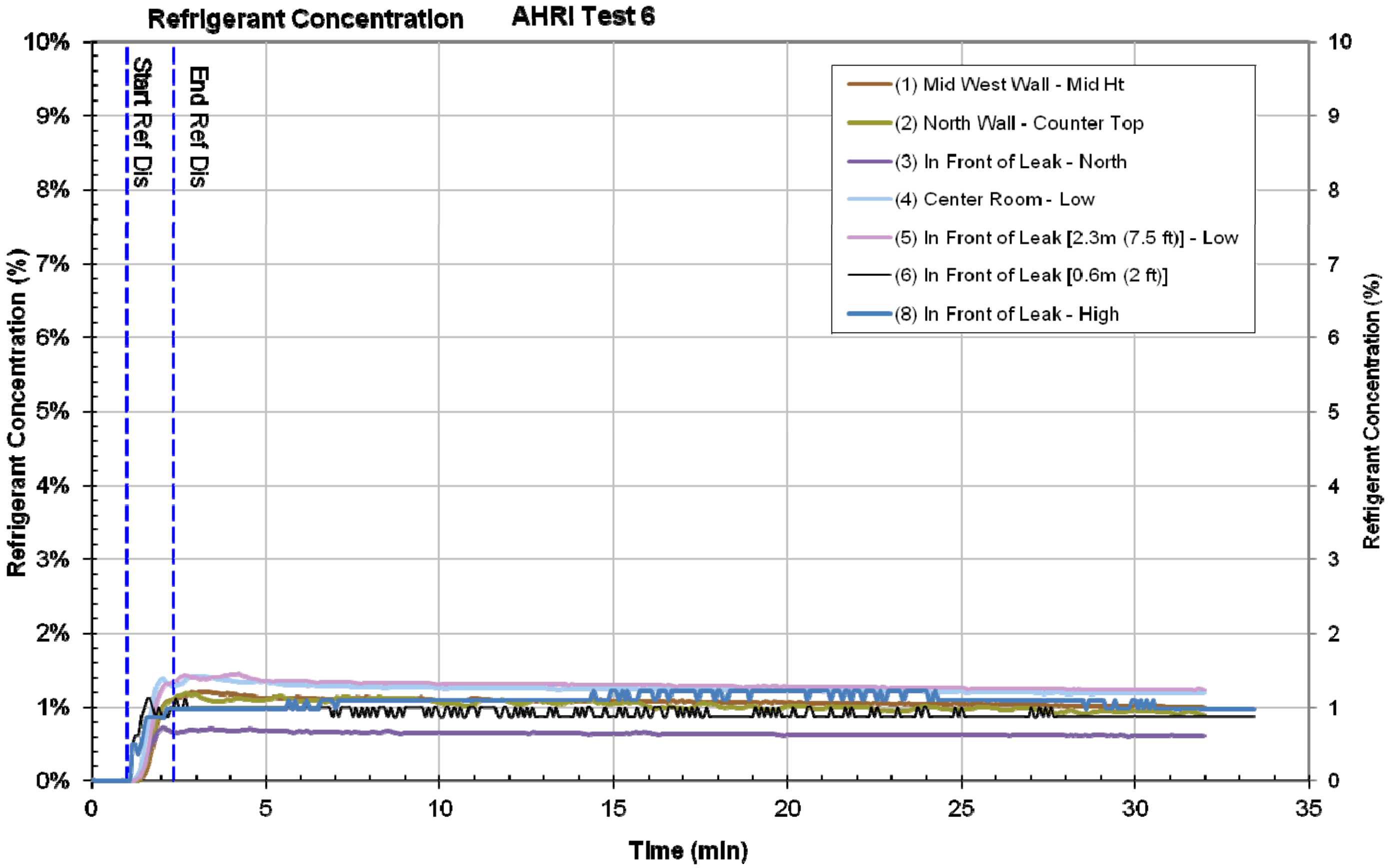
HFC-32 Concentrations During Garage Scenario Test



HFO-1234ze Cylinder Pressures During Garage Scenario Test



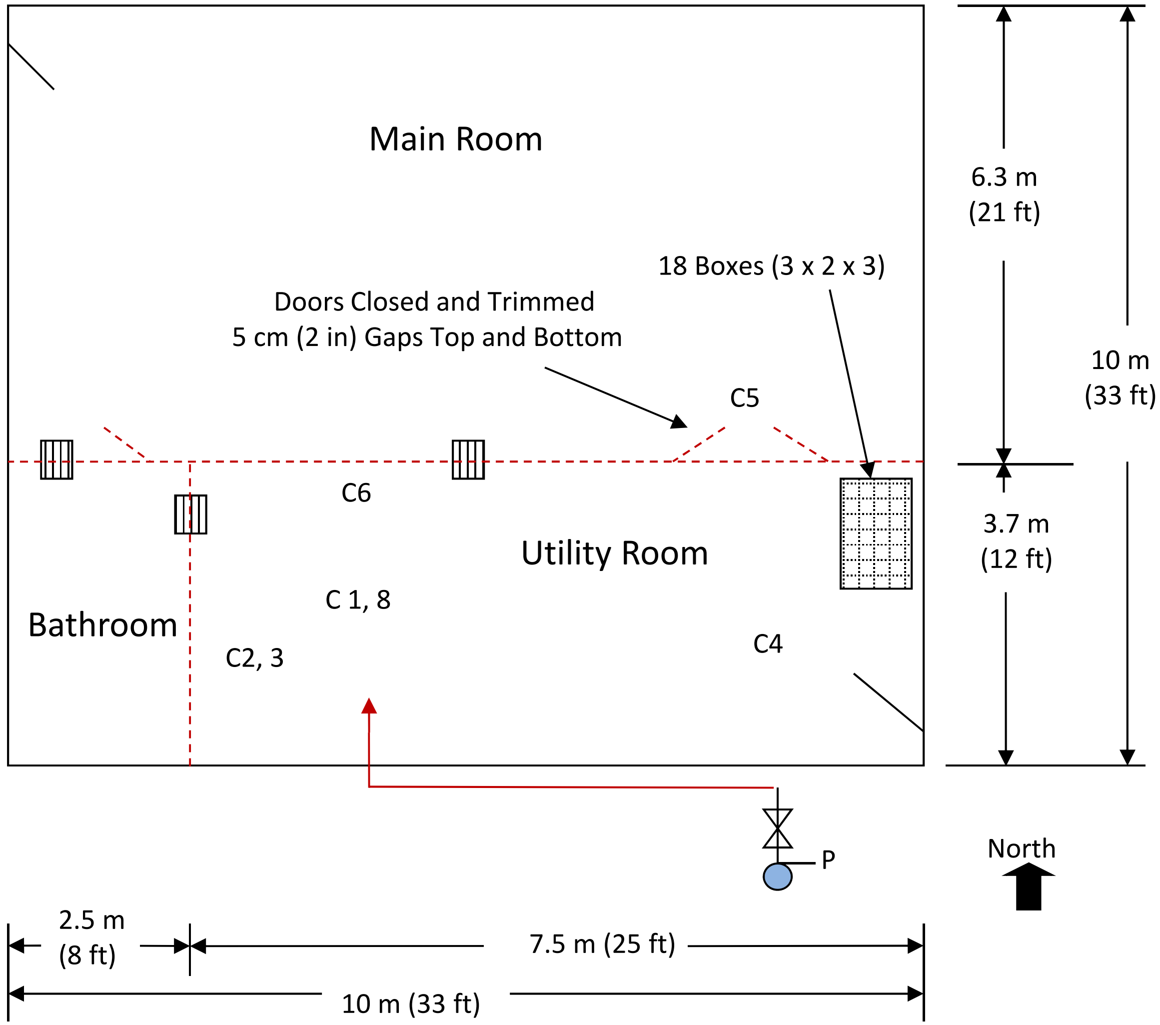
HFO-1234ze Concentrations During Garage Scenario Test



Garage Scenario Summary

- Similar Concentration Profiles for both refrigerants
  - Refrigerant concentrations quickly reached a plateau after the discharge of the refrigerant
- HFO-1234ze had lower concentrations reflecting higher vapor density
- HFC-32 had quicker discharge
  - liquid discharge time of 21 sec compared to 32 sec for HFO-1234ze
- HFC-32 concentrations below lower flammability limit of 14% at all monitored points
  - maximum of 3.02 % in front of leak low

Basement Scenario Schematic



▥ Vent Opening

● Discharge Cylinder

— Discharge Piping (8 mm (3/8") Copper Tubing)

P Pressure Measurement

▦ Cardboard Boxes – 0.45 m (1.5 ft) Cube

Concentration Measurements:
1-In Front of Leak [1.5m (5 ft)] - Low
2-In Front and West of Leak – Low
3-In Front and West of Leak – High
4-In Front and East of Leak – Low
5-Beyond Door [0.3m (1ft)] - Low
6-In Front of Leak – Opposite Wall
8-In Front of Leak – High

Basement Scenario Photographs

Facing West

Trimmed Doors

Facing East

Basement Scenario Release and Sampling Point Coordinates

Point	Description	West (X)		North (Y)		Elevation (Z)	
		[m]	[ft]	[m]	[ft]	[m]	[ft]
	Release Point	5.7	18.7	0.5	1.5	0.6	2.0
1	In Front of Leak [1.5m (5 ft)] - Low	5.7	18.7	2.0	6.5	0.2	0.5
2	In Front and West of Leak - Low	7.5	24.7	2.3	7.5	0.2	0.5
3	In Front and West of Leak - High	7.5	24.7	2.3	7.5	0.8	2.7
4	In Front and East of Leak - Low	1.2	4.0	1.3	4.3	0.2	0.5
5	Beyond Door [0.3m (1 ft)] - Low	2.1	7.0	4.1	13.3	0.2	0.5
6	In Front of Leak - Opposite Wall	5.7	18.7	3.7	12.0	0.5	1.5
8	In Front of Leak - High	5.7	18.7	2.0	6.5	1.5	5.0

Basement Scenario Refrigerant Release Summary

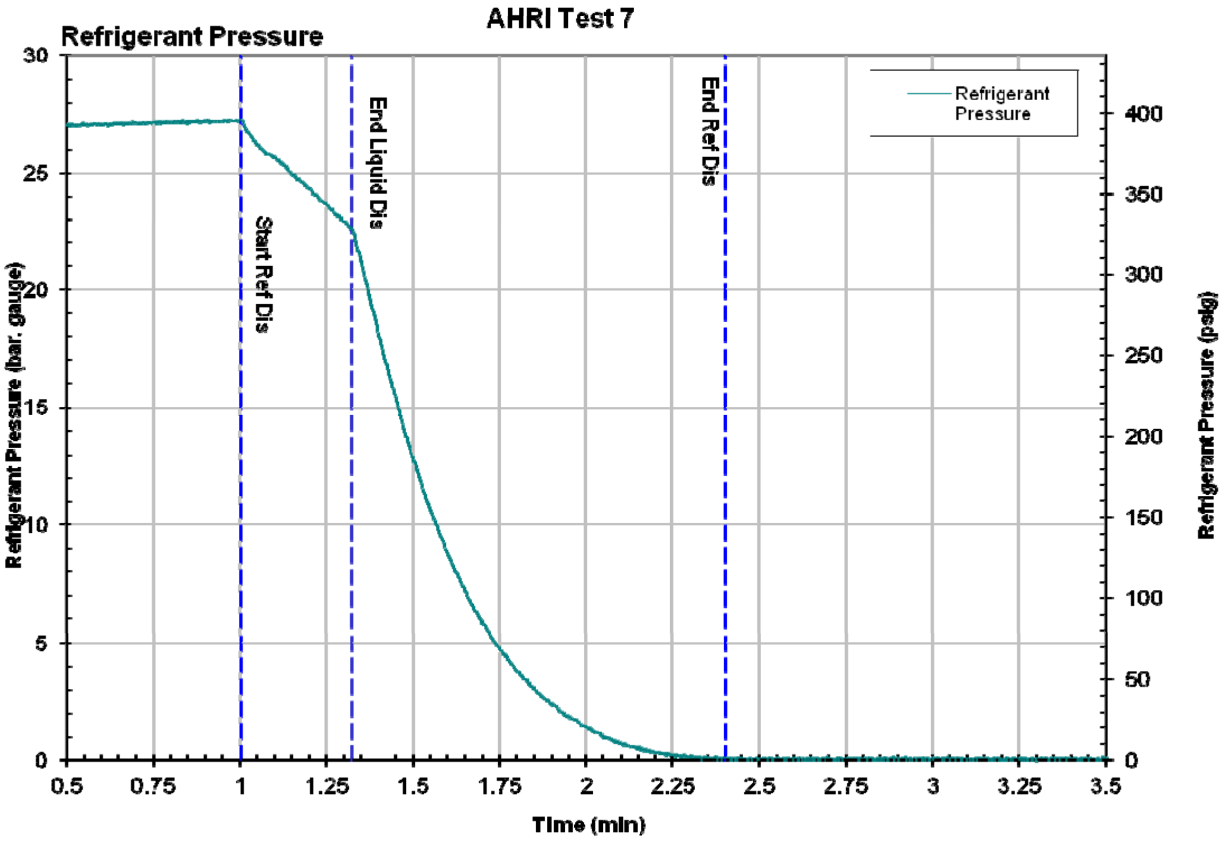
Test	Refrigerant	Refrig. Discharge Time		Refrigerant Pressures				Refrigerant Flow Rate (Liquid)*	
		Liquid	Total	Maximum		Ave Over Discharge (Total)			
		[sec]	[sec]	[bar]	[psig]	[bar]	[psig]	[g/s]	[lb/s]
AHRI Test 7	HFC-32	19.2	84	27.3	396	10.1	147	159	0.35
AHRI Test 8	HFO-1234ze	32.4	82.2	8.0	116	4.1	60	94	0.21
AHRI Test 9	HFO-1234ze	42	102	8.2	119	4.4	64	73	0.16
AHRI Test 10	HFO-1234ze	31.8	81	8.5	124	4.4	63	96	0.21
AHRI Test 11	HFO-1234ze	39	102	9.2	133	4.7	68	79	0.17

*Refrigerant flow rate based on 90% of mass delivered during liquid discharge

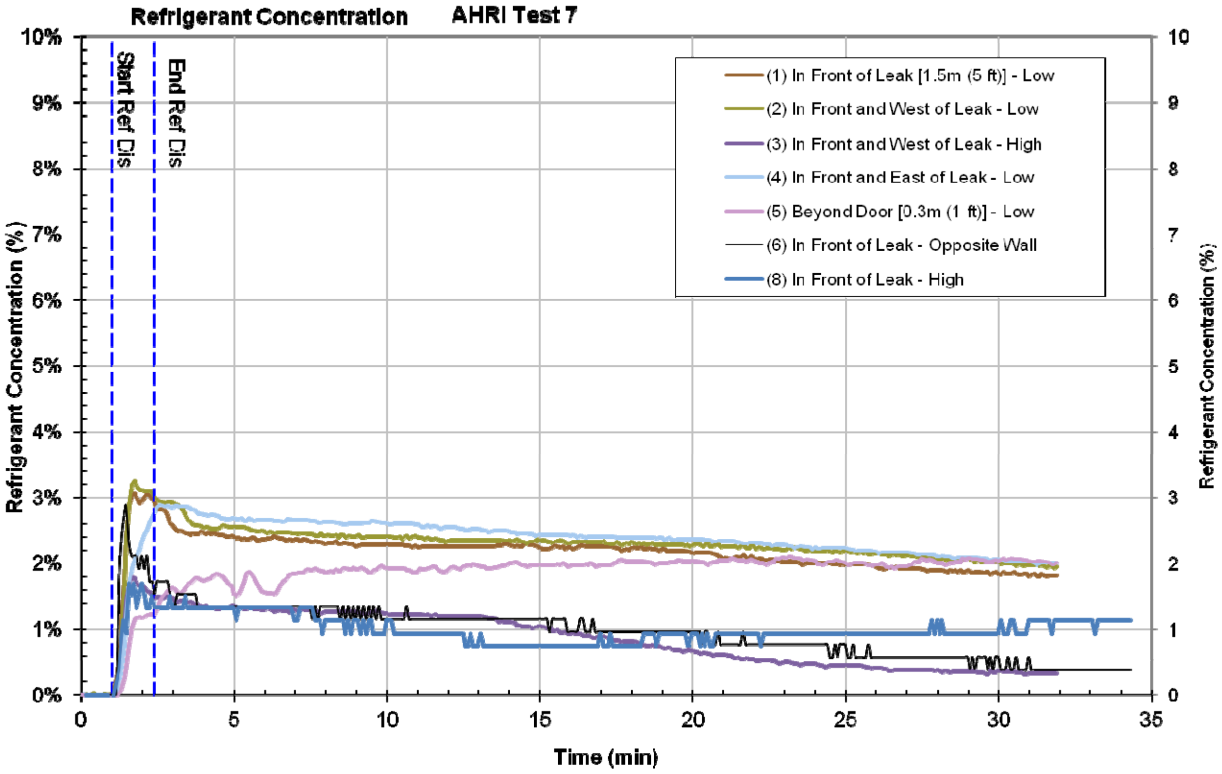
Basement Scenario Concentration Summary

Sampling Point			HFC-32	HFO-1234ze		
Test			AHRI Test 7	AHRI Test 8	AHRI Test 9	AHRI Test 11
(1) In Front of Leak - Low	Maximum	[%]	3.06	1.57	1.35	1.47
	5 min Average	[%]	2.41	1.27	1.16	1.27
	30 min Average	[%]	2.19	1.10	1.05	1.15
(2) In Front and West of Leak - Low	Maximum	[%]	3.26	1.56	1.46	1.49
	5 min Average	[%]	2.54	1.32	1.20	1.29
	30 min Average	[%]	2.32	1.20	1.10	1.19
(3) In Front and West of Leak - High	Maximum	[%]	1.79	0.77	0.82	0.83
	5 min Average	[%]	1.33	0.66	0.65	0.70
	30 min Average	[%]	0.89	0.35	0.36	0.43
(4) In Front and East of Leak - Low	Maximum	[%]	2.89	1.48	1.31	1.03
	5 min Average	[%]	2.42	1.26	1.11	0.88
	30 min Average	[%]	2.38	1.23	1.12	0.85
(5) Beyond Door [0.3m (1 ft)] - Low	Maximum	[%]	2.11	1.10	1.02	0.59
	5 min Average	[%]	1.41	0.63	0.63	0.30
	30 min Average	[%]	1.88	0.98	0.88	0.46
(6) In Front of Leak - Opposite Wall	Maximum	[%]	2.88	1.73	1.49	1.49
	5 min Average	[%]	1.53	0.91	0.98	1.00
	30 min Average	[%]	1.03	0.54	0.64	0.71
(8) In Front of Leak - High	Maximum	[%]	1.70	0.98	0.86	0.98
	5 min Average	[%]	1.27	0.77	0.67	0.76
	30 min Average	[%]	0.99	0.59	0.55	0.48

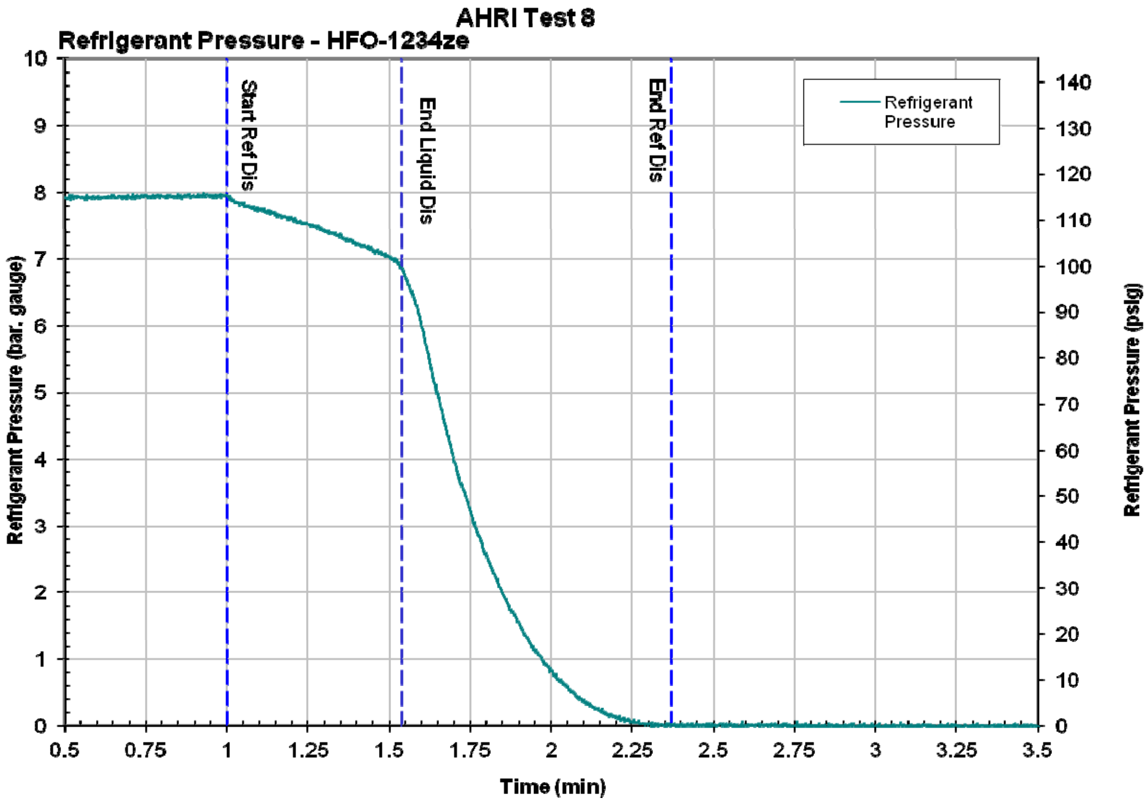
HFC-32 Cylinder Pressures During Basement Scenario Test



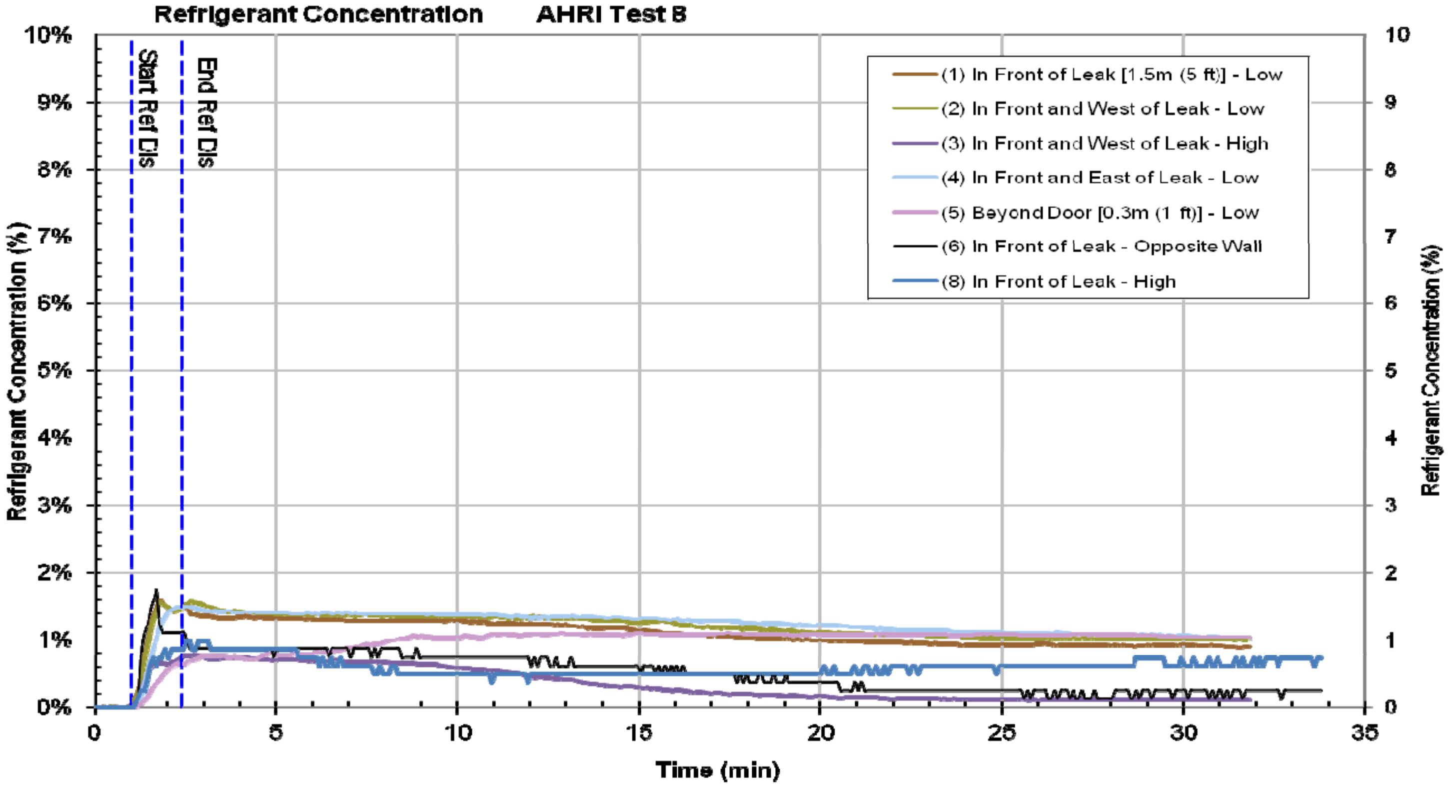
HFC-32 Concentrations During Basement Scenario Test



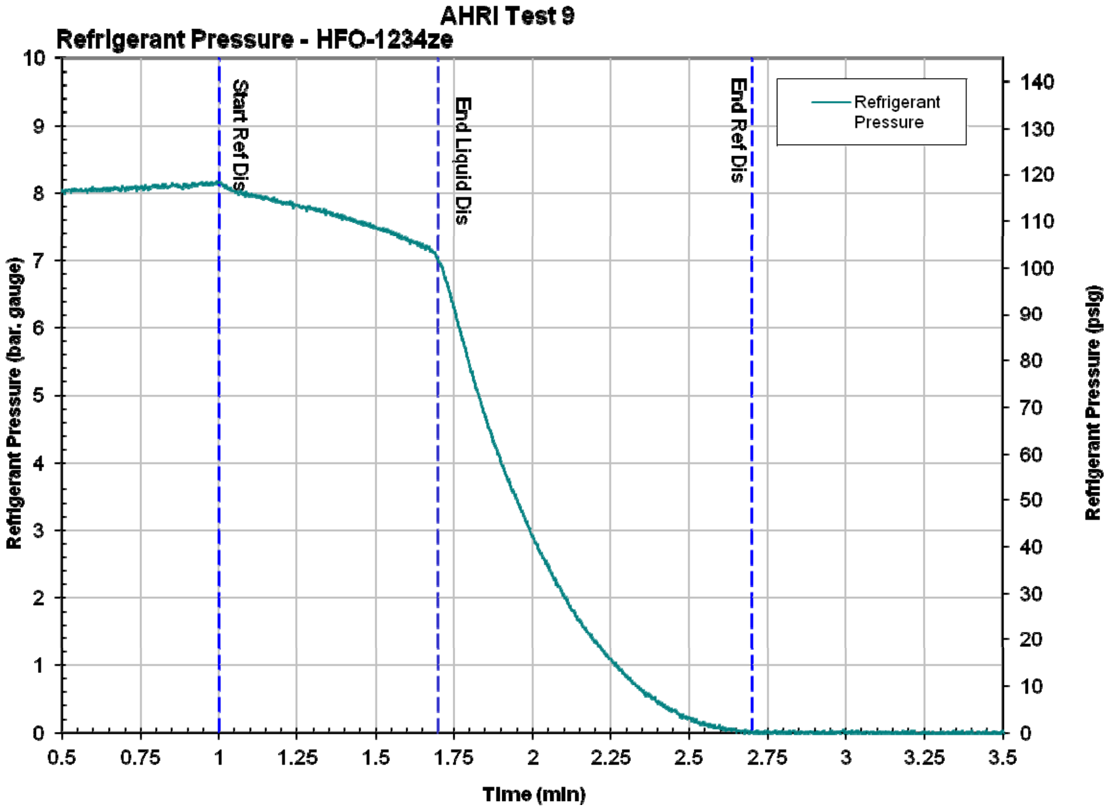
HFO-1234ze Cylinder Pressures During Basement Scenario Test



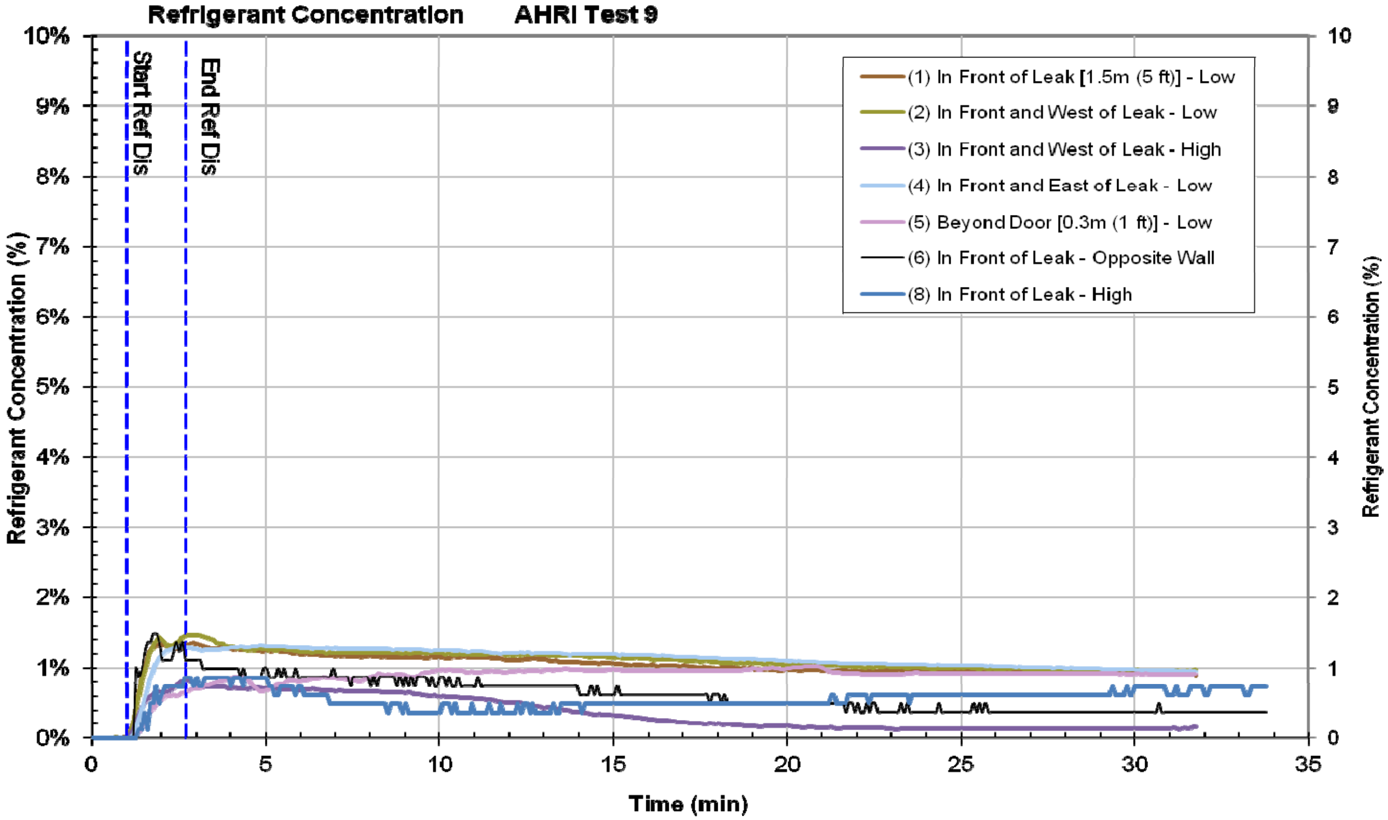
HFO-1234ze Concentrations During Basement Scenario Test



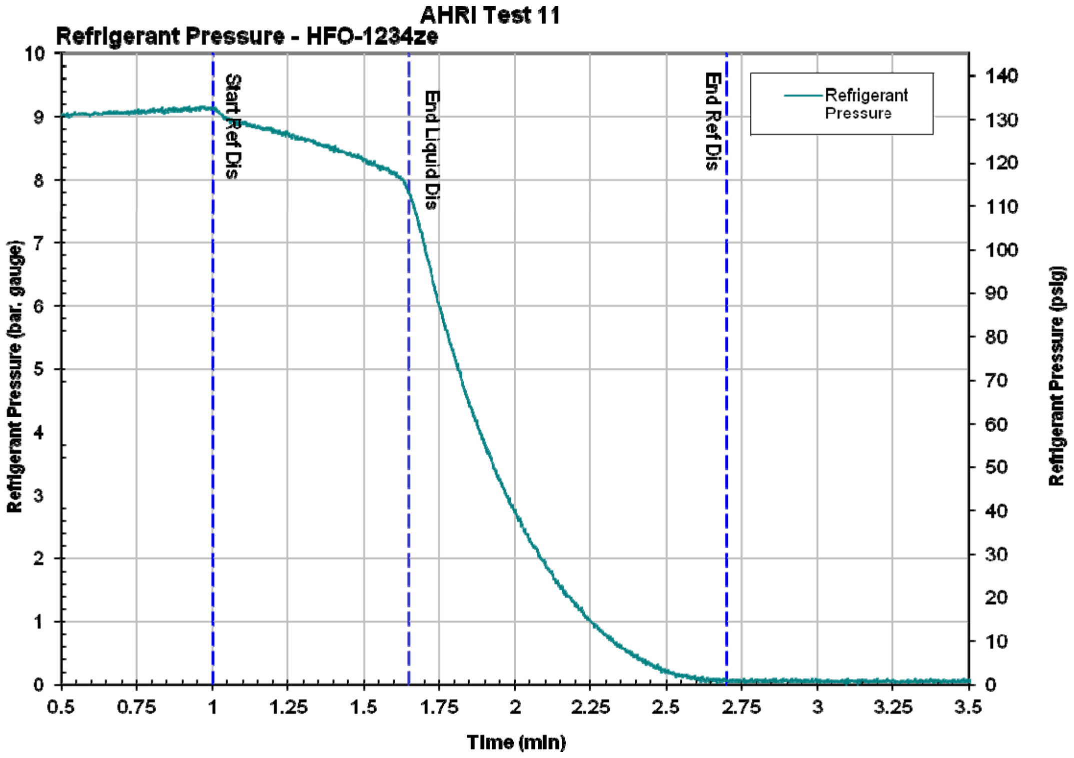
HFO-1234ze Cylinder Pressures During Basement Scenario Test (1st Repeat)



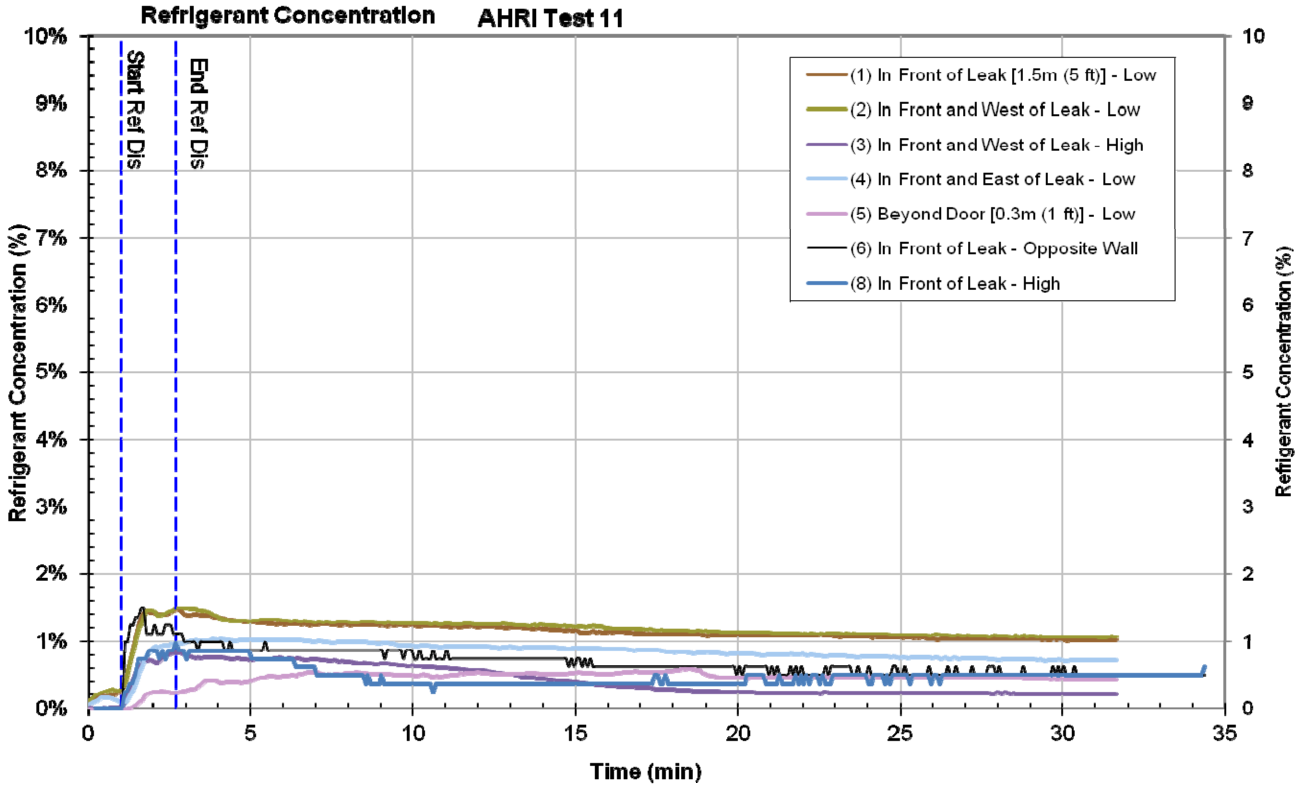
HFO-1234ze Concentrations During Basement Scenario Test (1st Repeat)



HFO-1234ze Cylinder Pressures During Basement Scenario Test (2nd Repeat)



HFO-1234ze Concentrations During Basement Scenario Test (2nd Repeat)



Reproducibility of Results

(repeat tests using HFO-1234ze and basement set up)

Sampling Point			HFO-1234ze				Standard Deviation
Test			AHRI Test 8	AHRI Test 9	AHRI Test 11	Mean Value	[%]
(1) In Front of Leak - Low	Maximum	[%]	1.57	1.35	1.47	1.46	9.2%
	5 min Average	[%]	1.27	1.16	1.27	1.23	5.2%
	30 min Average	[%]	1.10	1.05	1.15	1.10	3.9%
(2) In Front and West of Leak - Low	Maximum	[%]	1.56	1.46	1.49	1.50	4.1%
	5 min Average	[%]	1.32	1.20	1.29	1.27	5.0%
	30 min Average	[%]	1.20	1.10	1.19	1.16	4.2%
(3) In Front and West of Leak - High	Maximum	[%]	0.77	0.82	0.83	0.81	2.7%
	5 min Average	[%]	0.66	0.65	0.70	0.67	2.0%
	30 min Average	[%]	0.35	0.36	0.43	0.38	3.5%
(4) In Front and East of Leak - Low	Maximum	[%]	1.48	1.31	1.03	1.28	18.4%
	5 min Average	[%]	1.26	1.11	0.88	1.08	15.5%
	30 min Average	[%]	1.23	1.12	0.85	1.07	16.1%
(5) Beyond Door [0.3m (1 ft)] - Low	Maximum	[%]	1.10	1.02	0.59	0.90	22.4%
	5 min Average	[%]	0.63	0.63	0.30	0.52	15.3%
	30 min Average	[%]	0.98	0.88	0.46	0.77	22.7%
(6) In Front of Leak - Opposite Wall	Maximum	[%]	1.73	1.49	1.49	1.57	11.7%
	5 min Average	[%]	0.91	0.98	1.00	0.96	4.0%
	30 min Average	[%]	0.54	0.64	0.71	0.63	7.0%
(8) In Front of Leak - High	Maximum	[%]	0.98	0.86	0.98	0.94	5.8%
	5 min Average	[%]	0.77	0.67	0.76	0.73	4.3%
	30 min Average	[%]	0.59	0.55	0.48	0.54	4.2%

Basement Scenario Summary

- Similar Concentration Profiles for both refrigerants
  - The highest concentrations were in front of the leak (1) and near it at the 0.15m (0.5 ft) level (2). Concentrations at the opposite wall at the socket level rise sharply and then fall. The concentration in the adjacent room at 0.15m (0.5 ft) (5), beyond the closed doors increases slowly to match the other floor level concentration plateaus.
- HFO-1234ze had lower concentrations reflecting higher vapor density
- HFC-32 had quicker discharge
- HFC-32 concentrations below lower flammability limit of 14% at all monitored points
  - maximum of 3.26 % in front and west of leak low
- Standard Deviation (SD) <10% for most of the sampling points. The larger SD in the outer room (5) is not surprising given the small migration path (under the door) and the large room volume (even slight differences in air currents could be significant)

Summary

- 10 Tests Conducted
  - 2 Refrigerants: HFC-32 and HFO-1234ze
  - 4 Scenarios Representing Residential Settings
    - Main Floor
    - Attic
    - Garage
    - Basement

Summary

- Concentration Profiles Similar for Both Refrigerants
  - Peak Concentration during Refrigerant Discharge
  - Lower Plateau Concentration after End of Discharge
  - Gradual Decline over Thirty Minute Test Duration

Summary

- HFC-32 Concentrations Higher than HFO-1234ze due to Lower Vapor Density
  - Highest HFC-32 Concentration of 6.6% in Utility Closet during Main Floor Scenario
    - Lower than 14% Lower Flammability Limit for HFC-32
  - Highest HFO-1234ze Concentration of 3.61 in front of Leak during Attic Scenario
    - Slightly Higher Than 3.57% Measured in Utility Closet during Main Floor Scenario Test

Appendix C

Fault Trees and Input Values Table

Table C.1 Inputs Probabilities for Fault Trees

Event	Description	R-1234yf Value	R-1234ze Value	R32 Value	Remarks	Fault Tree
6	Probability of leak from within air handler (per year)	4.5E-03	4.5E-03	4.5E-03	Value from Goetzler et al. (1998) based on data by ADL. Discussion by the AHRI steering committee indicated no substantial basis for revising this value. Value is likely conservative for current equipment designs.	1-4,8,9
9	Sufficient refr release to attain flammable conc range in garage, air handler leak	2.0E-03	2.0E-03	2.0E-03	CFD and lab results show that R-32 and R-1234 did not produce flammable concentrations in the garage even in the case of a very large leak (except for right in front of the leak spot). Predicted concentrations were around 2-3%. The probability of a flammable concentration is therefore very low. It is not zero because more constricted spaces than those considered could produce such concentrations. The value is larger than for the attic because the basement space is likely to be smaller and predicted refrigerant concentrations were higher.	1
11	Unit is idle/off	0.6	0.6	0.6	Goetzler et al. used a value of 0.8 for the NE US. Although climatic conditions differ across the country, these should tend to equalize for heat pumps (more use for heating in the North, more use for cooling in the South). The group decided on a value of 0.6 to reflect more widespread conditions.	1-6,8
18	Probability of leak from inlet piping to air handler (per year)	1.0E-04	1.0E-04	1.0E-04	Value from Goetzler et al. (1998) based on data by ADL. Discussion by the AHRI steering committee indicated no substantial basis for revising this value. Value is likely conservative for current equipment designs.	1-4
21	Sufficient refr release to attain flammable conc range in garage, inlet piping leak	3.0E-03	3.0E-03	3.0E-03	Based on the same rationale as the air handler leak in the garage but 50% increased probability due to the larger size of piping.	1
30	Electrostatic air cleaner spark occurs of sufficient energy	0	0	1.0E-03	Calculations conducted by a manufacturer indicate that the energy generated by sparks in an electrostatic air cleaner is on the order of 1.75 mJ. This is several orders of magnitude less than the MIE of 1234yf and 1234ze and thus the probability for these is zero. The MIE of R-32 is between 32 and 100 mJ (Minor/Spatz presentation 1/23/08; Clodic, undated). The probability that the spark source is sufficient to ignite R-32 is probably still extremely small, perhaps 1E-3.	1-4
31	HVAC electronic- related sparks occur of sufficient energy	2.5E-01	2.5E-01	2.5E-01	This usually involves a 240V line. Studies by Honeywell indicate that electric faults (arcs) in this energy range will ignite refrigerants about 25% of the time.	1-4
32	HVAC-related spark present at correct place	1.0	1.0	1.0	Presumably a high value since it will be essentially co-located with the leak.	1-4
33	HVAC-related spark present in garage at correct time	4.0E-06	4.0E-06	4.0E-06	Sparks will be of very short duration (seconds) but have an equal chance of occurring throughout the year. The controlling factor is the duration of time the refrigerant is in the flammable range. CFD modeling suggests that even when refrigerants are in the flammable range (e.g., R-32 in the utility closet with the door closed) , the refrigerant disperses to below the LFL within 1-2 minutes or less. That equates to a value of 4E-6 (2 minutes/525,600 minutes per year).	1-4
36	Non-HVAC related sparks in garage of sufficient energy	1.0E-04	1.0E-04	1.0E-04	Most owners will not conduct activities in their garage which could provide such sparks. 1 hour per year for the population on average. This is likely quite high as most individuals would not engage in this activity.	1
37	Non-HVAC spark in garage present at correct place	1.0E-03	1.0E-03	1.0E-03	CFD indicates that the region of flammability is extremely limited and adjacent to the air handler (while slightly larger for R-32, the difference is not so great that it would substantially affect the order-of-magnitude probability). It is very unlikely that an ignition source would be located in this area. The value here (0.001 for all three refrigerants) is larger than for the attic because ignition sources (due to human activity) may be more likely in the garage.	1
38	Non-HVAC spark in garage present at correct time	2.3E-04	2.3E-04	2.3E-04	Assume that activities generating sparks (welding, grinding) occur for a total of 2 hours per year. In the worst case, these occur in a single 2 hour period (likely not continuous but repeatedly). That is 2.3E-4.	1

Table C.1 Inputs Probabilities for Fault Trees

Event	Description	R-1234yf Value	R-1234ze Value	R32 Value	Remarks	Fault Tree
42	Flame source present in garage	4.5E-03	4.5E-03	4.5E-03	Pilot lights typically have flame arrestors which would need to be removed and not reinstalled in order to pose a credible ignition source (equivalent to the human error probability of 1E-3). The other possibility is the presence of a gas furnace burner as part of a dual fuel system. According to the US Census (2008) 60 million owned homes list "electric heat pump" or "warm air furnace" as their primary heating equipment. 533,000 owned homes list either of these as "other heating equipment" (0.9%) (i.e., in addition to the primary equipment). However, not all of these are cases where each is present (e.g., some homes may have heat pumps and electric baseboard heaters or steam systems). We thus assume 0.45% (4.5E-3).	1
43	Flame source in garage present at correct place	1.0E-03	1.0E-03	1.0E-03	CFD indicates that the region of flammability is extremely limited and adjacent to the air handler (while slightly larger for R-32, the difference is not so great that it would substantially affect the order-of-magnitude probability). It is very unlikely that a flame ignition source would be located in this area. The value here (0.001 for all three refrigerants) is larger than for the attic because ignition sources (due to human activity) may be more likely in the garage.	1
44	Flame source in garage present at correct time	0.05	0.05	0.05	For constant sources (e.g. a pilot light), this value would be 1.0 but discussions have suggested this is not a credible ignition source for the refrigerant in the room. For other sources (e.g., a gas burner) assume it is working only 5% of the time (0.05).	1
45	Unit is located in garage	0.15	0.15	0.15	Based on OEM data supplied to AHRI.	1
51	Sufficient refr release to attain flammable conc range in basement, air handler leak	2.0E-03	2.0E-03	2.0E-03	CFD results show that R-32 and R-1234, even in the case of a very large leak, did not produce flammable concentrations in the basement (except for a narrow plume 0.7 m long in front of the leak location). Predicted concentrations were around 2-4%. The probability of a flammable concentration in the basement is low. It is not zero because more constricted spaces than those considered could produce such concentrations. The value (0.002 for all 3 refrigerants) is larger than for the attic because the basement space is likely to be smaller and predicted refrigerant concentrations were higher.	2
53	Sufficient refr release to attain flammable conc range in basement, inlet piping leak	3.0E-03	3.0E-03	3.0E-03	Based on the same rationale as the air handler leak in the basement but 50% increased probability due to the larger size of piping.	2
60	Non-HVAC related sparks of sufficient energy in basement (e.g., owner activities)	1.0E-04	1.0E-04	1.0E-04	Most owners will not conduct activities in their basement which could provide such sparks. 1 hour per year for the general population. This is likely quite high as most individuals would not engage in this activity.	2
61	Non-HVAC spark in basement present at correct time	2.3E-04	2.3E-04	2.3E-04	Assume that activities generating sparks (welding, grinding) occur for a total of 2 hours per year. In the worst case, these occur in a single 2 hour period (likely not continuous but repeatedly). That is 2.3E-4.	2
62	Non-HVAC spark in basement present at correct place	1.0E-03	1.0E-03	1.0E-03	CFD indicates that the region of flammability is extremely limited and adjacent to the air handler (while slightly larger for R-32, the difference is not so great that it would substantially affect the order-of-magnitude probability). It is very unlikely that an ignition source would be located in this area. The value (0.001 for all three refrigerants) is larger than for the attic because ignition sources (due to human activity) may be more likely in the basement.	2
65	Flame source present in basement sufficient to ignite refrigerant	4.5E-03	4.5E-03	4.5E-03	Pilot lights typically have flame arrestors which would need to be removed and not reinstalled in order to be credible (human error rate, 1E-3). The other possibility is the presence of a gas furnace burner as part of a dual fuel system. According to the US Census (2008) 60 million owned homes list "electric heat pump" or "warm air furnace" as their primary heating equipment. 533,000 owned homes list either of these as "other heating equipment" (0.9%) (i.e., in addition to the primary equipment). However, not all of these are cases where each is present (e.g., some homes may have heat pumps and electric baseboard heaters or steam systems). A value reduced by 50% (0.45%, 4.5E-3) was therefore used.	2

Table C.1 Inputs Probabilities for Fault Trees

Event	Description	R-1234yf Value	R-1234ze Value	R32 Value	Remarks	Fault Tree
66	Flame source in basement present at correct place	1.0E-03	1.0E-03	1.0E-03	CFD indicates that the region of flammability is extremely limited and adjacent to the air handler (while slightly larger for R-32, the difference is not so great that it would substantially affect the order-of-magnitude probability). It is very unlikely that a flame ignition source would be located in this area. The value here (0.001 for all three refrigerants) is larger than for the attic because ignition sources may be more likely in the basement (e.g., unshielded gas utilities).	2
67	Flame source in basement present at correct time	0.1	0.1	0.1	For constant sources (e.g. a pilot light), this value would be 1.0 but OEM discussions have suggested this is not a credible ignition source for the refrigerant in the room. For other sources (e.g., a gas burner) assume it is working only 10% of the time (0.1).	2
68	Unit is located in basement	0.3	0.3	0.3	Based on OEM data supplied to AHRI.	2
75	Sufficient refr release to attain flammable conc range in attic, air handler leak	1.0E-03	1.0E-03	1.0E-03	CFD and lab results show that R-32 and R-1234 did not produce flammable concentrations in the attic (except for right in front of the leak spot) even with a very large leak. Predicted concentrations were around 1%. So the probability is very low (i.e., 0.001 for all 3 refrigerants). It is not zero because more constricted spaces than those we considered could produce such concentrations.	3
83	Sufficient refr release to attain flammable conc range in garage, inlet piping leak	1.5E-03	1.5E-03	1.5E-03	Based on the same rationale as the air handler leak in the attic but 50% increased probability due to the larger size of piping.	3
94	Non-HVAC related sparks of sufficient energy in attic	5.3E-04	5.3E-04	5.3E-04	According to the US NRC, the typical failure rate for wire shorts is 3E-7 per operating hour. Adjusting for the operating time of the unit (1752 hours or 20% per year) yields 5.3E-4 per year. All three refrigerants are assumed to be equally likely to be ignited by such a short.	3
95	Non-HVAC spark in attic present at correct place	1.0E-06	1.0E-06	1.0E-06	CFD indicates that the region of flammability is extremely limited in the attic and adjacent to the air handler (for all 3 refrigerants). It is very unlikely that a non-HVAC ignition source would be located in this area.	3
96	Non-HVAC spark in attic present at correct time	1.0E-05	1.0E-05	1.0E-05	Sparks will be of very short duration (seconds) but have an equal chance of occuring throughout the year. The controlling factor is the duration of time the refrigerant is in the flammable range. Sparks will be of very short duration (seconds) but have an equal chance of occuring throughout the year. The controlling factor is the duration of time the refrigerant is in the flammable range. CFD modeling suggests that the refrigerant will only be in the flammable range (near the leak spot) while the leak is actually occuring. After this time it will rapidly disperse. Assuming a leak duration of 5 minutes (a relatively slow leak compared to those modeled) yields a probability of (5 minutes/525,600 minutes per year) 1E-5	3
97	Sufficient flame source present in attic	0	0	0	The group deterimined that the likelihood of having a flame source (e.g., utility with unshielded pilot light, individual engaged in welding) is essentially zero.	3,6
98	Unit is located in attic	0.35	0.35	0.35	Based on OEM data supplied to AHRI.	4
104	Sufficient refr release to attain flammable conc range in utility closet, air handler leak	0.1	0.1	0.5	CFD and lab results show that R-1234 did not produce flammable concentrations at medium or small leaks (except for right in front of the leak location). With a very large leak (78 g/s), the LFL was exceeded at some portion of the utility closet when the door was closed. But such a large leak is unlikely. It is not a zero probability because more constricted spaces than those considered could produce such concentrations and utility closet may be particularly crowded. The CFD and lab results indicated that R-32 did produce flammable concentrations in the utility closet with the large leak. The data would suggest that at least for the door closed scenario, smaller leaks would also produce flammable concentrations in some portion of the UC. The AHRI steering committee decided on values of 0.1 for R-1234yf and R-1234ze and 0.5 for R-32.	4
106	Sufficient refr release to attain flammable conc range in utility closet, inlet piping leak	0.15	0.15	0.75	Based on the same rationale as the air handler leak for the utility closet but 50% increased probability due to the larger size of piping. Values of 0.15 for R-1234yf and R-1234ze and 0.75 for R-32.	4

Table C.1 Inputs Probabilities for Fault Trees

Event	Description	R-1234yf Value	R-1234ze Value	R32 Value	Remarks	Fault Tree
112	Flame source present in utility closet	5.6E-03	5.6E-03	5.6E-03	Probability that such a source is present., e.g., a gas water heater or gas clothes dryer. Other flame sources (e.g., a homeowner using a propane torch) would not be expected in a utility closet. It is assumed that if a home has a utility closet, appliances will be located there. The probability of having a utility closet is tied into the probability an hair handler is located there (Event #115). However, not all appliances are gas. According to the Natural Gas Supply Association (2011), 56% of US homes are supplied with natural gas. Although not all homes with supplied natural gas will use it in appliances, a value of 0.56 is used conservatively. However, most gas appliances have a shielded flame to prevent ignition of gas leaks. Only when the shielding is absent (due to an old unit, more than approximately 15 years old), fails or is intentionally removed with the flame source be able to ignite leaked refrigerant. The group judged this likely in only 1 in 100 cases. Thus 0.01 x 0.56 = 0.0056.	4
113	Flame source in utility closet present at correct place	0.5	0.5	0.9	Events 104 and 106 address whether the leak is sufficiently large to produce a flammable concentration in the utility closet. This value relates to how large the flammable zone will be and whether it might intersect a potential ignition source. CFD modeling indicates that if a leak is sufficient large, R-32 can generate flammable concentrations inside a UC with the door closed or open. With the door closed, the LFL is exceeded in much of the utility closet, particularly in the lower portion of the closet. The earlier study by Goetzler et al. also suggest more modest leaks could produce flammable concentrations in small spaces. Regarding R-1234yf and R-1234ze, CFD modeling indicates that for very large leaks (78 g/s) flammable concentrations are generated in portions of the utility closet (albeit briefly) when the utility closet door is closed. When the door is open flammable concentrations are not reached. A value of 0.5 (the ignition source could be in an area where the LFL is not exceeded or the door could be partially open) is used for both R-1234yf and R-1234ze, whereas the probability for R-32 is 0.9. A utility closet larger than that used in the modeling could produce lower concentrations that do not exceed the LFL.	4
114	Flame source in utility closet present at correct time	0.05	0.05	0.05	For constant sources (e.g. a pilot light), this value would be 1.0 but discussions have suggested this is not a credible ignition source for the refrigerant in the room. For other sources (e.g., a gas burner) assume it is working only 5% of the time (0.05).	4
115	Unit is located in utility closet	0.2	0.2	0.2	Based on OEM data supplied to AHRI.	4,6
119	Failure of electrical feed through plug (per unit, per year)	9.0E-05	9.0E-05	9.0E-05	According to the Reliability Information Analysis Center (RIAC, an organization sponsored by the US Department of Defense Technical Information Center) Non-Electronic Parts Reliability Database, the failure rate for electrical feedthrough connectors was less than 5 per 100 million operating hours (i.e., no failures were observed in this timeframe so it constitutes a worst-case failure estimate). Adjusting for the operating time of the unit (1752 hours or 20% per year) yields 9E-5 per year. All three refrigerants are assumed to be equally likely to be ignited by such a short	5
120	Leak is large enough to produce a flammable refrigerant concentration in the condensing unit	1.0	1.0	1.0	The refrigerant could be at high enough concentration to be above the LFL at some location within the condensing unit. Not likely to be significantly related to the properties of the refrigerant given the small volume involved. Assumed a value of 1.0. Note that the probability the refrigerant is above the UFL is not included in this scenario, a conservative approach.	5
123	Plug fault is of sufficient energy to ignite refrigerant	1.0	1.0	1.0	Conservatively assumed to be 1.0, although this is uncertain, particular for R-1234yf and R-1234ze which have particularly high minimum ignition energies.	5
125	Release is not so turbulent as to quench refrigerant flame	0.2	0.2	1.0	This is an important issue for R-1234yf and R-1234ze, both of which produce highly unstable flames. The group assumed a value of 0.2 for both refrigerants. Because R-32 produced a more stable flame a value of 1.0 is used. Note the inverse of this probability is the probability the flame is quenched and does not propagate (0.8 for R-1234yf and R-1234ze and 0 for R-32).	5

Table C.1 Inputs Probabilities for Fault Trees

Event	Description	R-1234yf Value	R-1234ze Value	R32 Value	Remarks	Fault Tree
127	Leak from outdoor unit, other than feed through plug fault (per unit per year)	4.5E-03	4.5E-03	4.5E-03	4.5e-3 from Goetzler et al. (1998). 4.5E-3 from Goetzler et al. (1998). May be conservative given that according to US NRC, a typical rupture rate for pipes is 1E-9/hr and the failure rate for welds is 3 E-9 per hr. However, the group determined that there was no substantive basis for revising this number.	5
132	No dispersion by wind	0.06	0.06	0.06	Data from NOAA (undated) indicate that in the U.S., still air conditions prevail, on average, approximately 6% of the time.	5,R
143	Box around electronics does not prevent flame propation to rest of refrigerant	1.0E-04	1.0E-04	1.0E-04	Assumes the box is poorly designed, defective or has been removed (i.e., the basic human error probability, 1E-3). Lowered to 1E-4 assuming the box is redesigned for use with 2L refrigerants.	5
144	Control system spark/arc occurs that is of sufficient energy	0.25	0.25	0.25	Usually involves a 240V line. Studies by Honeywell indicate that about 25% of arcs produced in this energy range will ignite these refrigerants.	5
147	Fault in fan motor	1.8E-05	1.8E-05	1.8E-05	Based on US NRC data for electrical shorts (wires), 1E-8 per operating hour, adjusted for the number of unit operation hours per year.	5
148	Fan spark is of sufficient energy	0.95	0.95	0.95	A fan spark which would have enough energy to ignite these refrigerants in most cases. The issue is whether refrigerant contacts the refrigerant (depends on casing).	5
154	Sufficient refrigerant released in AH leak to attain flammable concentration range in return air room	1.0E-04	1.0E-04	1.0E-04	This is the probability that the refrigerant leaking from the air handler reaches the flammable range anywhere within a hallway (or other adjacent room) supplying return air to a unit located in a utility closet. Thus the leak must be large enough to diffuse from the air handler, through the ductwork and into the return air room at a flammable concentration. Leaks this large must be due to faulty braze joints, which are rare, with a probability of perhaps 1 out of 10,000. The appropriateness of a small value is also supported by the CFD modeling which showed that only in a small confined space the size of a utility closet (unlikely to be used as a source of return air) is the LFL likely to be exceeded.	6
157	Sufficient concentration released in AH leak to attain flammable concentration range in return air room (attic/basement/garage)	1.0E-05	1.0E-05	1.0E-05	Similar to Event #154 but the probability is even smaller because the length of ductwork between the unit located in the attic, basement or garage and a return air room will be longer and thus present more opportunity for dilution.	6
159	Room has sufficient electric source	4.5E-06	4.5E-06	4.5E-06	Two types of electrical sources are theoretically possible, resistance sources (e.g., an electric baseboard heater) or electrical shorts/arcs. Studies have shown that a hot wire (simulating a resistance source) does not ignite these refrigerants. An electrical short or arc is a very rare event (3E-7 probability per hour [or 1.8E-5 per year] according to the US NRC). Studies by Honeywell using a 110V source show that 25% of the time, the spark is sufficient to ignite the refrigerant. This produces a probability of such a spark occurring per year at 4.5E-6 per year (i.e., 1.8E-5 x 0.25).	6
160	Room has sufficient flame source	0.1	0.1	0.1	This relates to where the return duct is located and whether the return air room has a flame source. For all three refrigerants, an open flame is a credible ignition source. These could include kitchens (e.g., gas stoves), living rooms (fireplaces), or dining rooms (fireplaces or candles). However, return air vents are unlikely to be located in kitchens. US statistics indicate that approximately 28% of homes have a useable fireplace (HPBA, undated; US census, 2001). Because return air vents may not necessarily be located in a room with a fireplace, the value is reduced to 0.10	6

Table C.1 Inputs Probabilities for Fault Trees

Event	Description	R-1234yf Value	R-1234ze Value	R32 Value	Remarks	Fault Tree
161	Ignition source present at relevant location	1.0E-04	1.0E-04	1.0E-04	A low value, 1E-4 for all three refrigerants, because a leak in the air handler will not migrate at high concentrations before being dispersed in the larger room. The CFD modeling indicates flammable concentrations of R-32, R-1234yf and R-1234ze only occurred in the confined utility closet (with door closed) and a small area of the adjacent kitchen. Thus flammable concentrations in the room connected by the return air ductwork are not expected because the refrigerant will be substantially diluted before reaching the room and only a small area near the vent, if that, would have enough refrigerant to be above the LFL. It is also the case that a combustion source (e.g., fireplace) is unlikely to be located next to a return air vent.	6
162	Ignition source present at relevant time	0.04	0.04	0.04	If we assume that utility pilot lights are protected in such a way that prevents their serving as a trigger for ignition, then the most relevant ignition sources are episodic, e.g., candles, gas stoves, fireplaces. Electrical sources (essentially wire shorts, are likely to be far less common). Assume that people spend one hour out of every day (on average) performing some activity involving use of a flame source. This yields a probability of 0.04.	6
164	Refrigerant leak inside wall from connections, piping, joints	1.0E-05	1.0E-05	1.0E-05	Goetzler et al. state that the probability of a leak from the inlet piping to the air handler is 1E-4. Since the piping inside the wall is better isolated from physical stresses (e.g., bangs, knocks), it seems that a probability 10 times lower is reasonable.	7
167	Leak is not dispersed by drafts in wall	1.0	1.0	1.0	It was assumed that no drafts occur in the wall.	7
168	Ignition source in wall sufficient to ignite refrigerant	0.01	0.01	0.10	The probability that an electrical short has SUFFICIENT energy to ignite the refrigerant must be low, particularly for yf and ze due to their high MIE. Perhaps 0.01 for R-1234yf and R-1234ze and 0.1 for R-32.	7
169	Wiring short occurs in wall	2.6E-03	2.6E-03	2.6E-03	The US NRC (1981) gives a general probability of a wire short (to ground) of 3E-7 per hour. This is equivalent to 2.6E-3 per year.	7
170	Sufficient ignition source occurs at same time as refrigerant leak (leak in wall)	6.0E-05	6.0E-05	6.0E-05	Assume the short lasts for only a few (e.g. , 30) seconds before a fuse or power breaker cuts off the power. Assume that refrigerant released by the leak would only be at a flammable concentration inside the wall for perhaps 30 minutes (being either above or below the range at other times). This larger time is the controlling factor because a brief spark occuring during this time period would be sufficient to bring about the event. There are 525,600 minutes per year. The probability that the spark occurs when the leaked refrigerant is in the flammable range is (30/525,600 = 6E-5). Note this assumes the leak and spark are independent events.	7
175	Room has sufficient ignition source (at any time/location)	4.7E-03	4.7E-03	4.7E-03	This relates to whether the return air room has a flame or electrical ignition source. Sources might include gas water heaters (with guard removed), gas ovens, gas ranges, gas fireplaces, or electrical shorts. The likelihood of a short will be far lower than that of having an intentional flame source operating. Approximately 51% of US homes have gas service (Natural Gas Supply Association, 2011). Assume such an appliance is used 15 minutes per day averaged over all rooms in the house (0.01). This is multiplied by 56% (probability the home has gas) and divided by 5 to account for not all rooms having such devices. (e.g., bedrooms, hallways).	8
179	Sufficient refrigerant released to attain flammable conc. range in air handler	5.0E-06	5.0E-06	1.0E-05	The great majority of leaks in the air handler will be small leaks which will not have sufficient leak rates to form flammable concentrations in the air handler. Leaks massive enough to create flammable concentrations in the air handler will be rare. This is consistent with the prior study by Goeztler et al. which showed that leaks in the air handler as high as approximately 1 g/s did not create flammable concentrations in the air handler. A value of 1E-5 is used for R-32 and a value half this large (5E-6) is used for R-1234ze and R-1234yf. The smaller value for ze and yf accounts for the operating pressures of these systems (roughly half as high) which is less likely to cause a massive leak.	8,9
180	Blower in air handler is NOT operating when unit is on	1.0E-04	1.0E-04	1.0E-04	This situation could occur if the unit was malfunctioning. A probability of 1E-4 was used based on expert judgment Note that the blower fault must occur in the same time period as the refrigerant leak.	9

Table C.1 Inputs Probabilities for Fault Trees

Event	Description	R-1234yf Value	R-1234ze Value	R32 Value	Remarks	Fault Tree
183	Unit restarted with blower coming on AFTER heat source	0.1	0.1	0.1	This might only occur for a minute or less in units designed not to blow cold air out of the ducts (i.e., the unit is designed to heat up before blowing air). A value of 0.1 is used to capture this limited time period.	9
184	Heat elements engaged and ignite refrigerant	0.17	0.17	0.17	On average, assume the furnace is used for heating 5 of 12 months per year (0.42). Assume that during those times, the heating elements are actually on 40% of the time (0.42*0.40=0.17). This assumes that when the heat elements are functioning, they have enough energy to ignite the refrigerant. (Note Goetzler et al. assumed ignition only in a white hot fault situation)	9
187	Probability unit is serviced per year	0.1	0.1	0.1	Goetzler et al. based on ADL proprietary data. OEMs indicate that approximately 10% of units are serviced in the first year of warranty.	R
190	Fraction of service calls involving brazing indoors	7.5E-02	7.5E-02	7.5E-02	Goetzler et al. gave a figure of 0.15 for all brazing based on ADL proprietary data. This value was dvided in half to obtain the indoor value.	R
192	Sufficient refrigerant involved (indoors)	1.0E-06	1.0E-06	1.0E-06	Goetzler et al. cited a value of 1E-3 for the refrigerant not being completely recovered (this value the typical human error probability). However, this is a critical part of the refrigerant repair activity that is probably much less likely to be ignored. One would have to completely disregard training to try and braze a joint without trying to recover the refrigerant. Even if the refrigerant were completely recovered, there may not be enough to produce a flammable concentration. Use of existing refrigerants that are flammable under pressure when mixed with air indicates the likelihood of such events are extremely low.	R
193	No dispersion by indoor air currents (e.g., fan)	0.9	0.9	0.9	Occupants are unlikely to have a fan operating in the furnace area but might do so for the benefit of the service person in particularly hot weather.	R
194	Serviceperson uses brazing torch at relevant time indoors	1.0E-04	1.0E-04	1.0E-04	Related to the fraction of time during the service call when the individual is brazing. Assume brazing activity lasts for 1 minute. The duration of time when the refrigerant is in the flammable range is going to be quite small. CFD modeling suggests even in the utility closet, this may only be approximately 1 minute.	R
198	Fraction of service calls involving brazing outdoors	0.07	0.07	0.07	Goetzler et al. gave a figure of 0.15 for all brazing based on ADL proprietary data. This value was dvided in half to obtain the outdoor value.	R
200	Sufficient refrigerant involved (outdoors)	1.0E-06	1.0E-06	1.0E-06	Goetzler et al. gave a figure of 1E-3 for refrigerant not completely recovered (typical human error rate). However, this is a critical part of the refrigerant repair activity that is probably much less likely to be ignored. One would have to completely disregard training to try and braze a joint without trying to recover the refrigerant. Even if the refrigerant were completely recovered, there may not be enough to produce a flammable concentration. Use of existing refrigerants that are flammable under pressure when mixed with air indicates the likelihood of such events are extremely low.	R
202	Serviceperson uses brazing torch at relevant time outdoors	1.0E-04	1.0E-04	1.0E-04	Related to the fraction of time during the service call when the individual is brazing. Assume brazing activity lasts for 1 minute. Duration of time when the refrigerant is in the flammable range is going to be quite small, perhaps just a few minutes. Overall, a likely value might be 0.0001.	R
207	Fraction of service calls involving charging	0.15	0.15	0.15	Based on Goetzler et al., ADL proprietary data	R
209	Serviceperson removes hose without closing cylinder valve	1.0E-03	1.0E-03	1.0E-03	Based on Goetzler et al. which employed a typical human error probability of 1E-3.	R
210	Initial charge vented to atmosphere	0.01	0.01	0.05	Goetzler et al. used 0.05. However, flammability and price will be motivating factors that change behavior. Refer to Event 215.	R
212	Fraction of service calls that involve recovery	0.15	0.15	0.15	Recovery is only necessary when one of the service valves is faulty and/or both indoor and outdoor portions of unit have to be replaced.	R
214	Leak while recovering to a closed container	1.0E-03	1.0E-03	1.0E-03	Based on Goetzler et al. which employed a typical human error probability of 1E-3.	R

Table C.1 Inputs Probabilities for Fault Trees

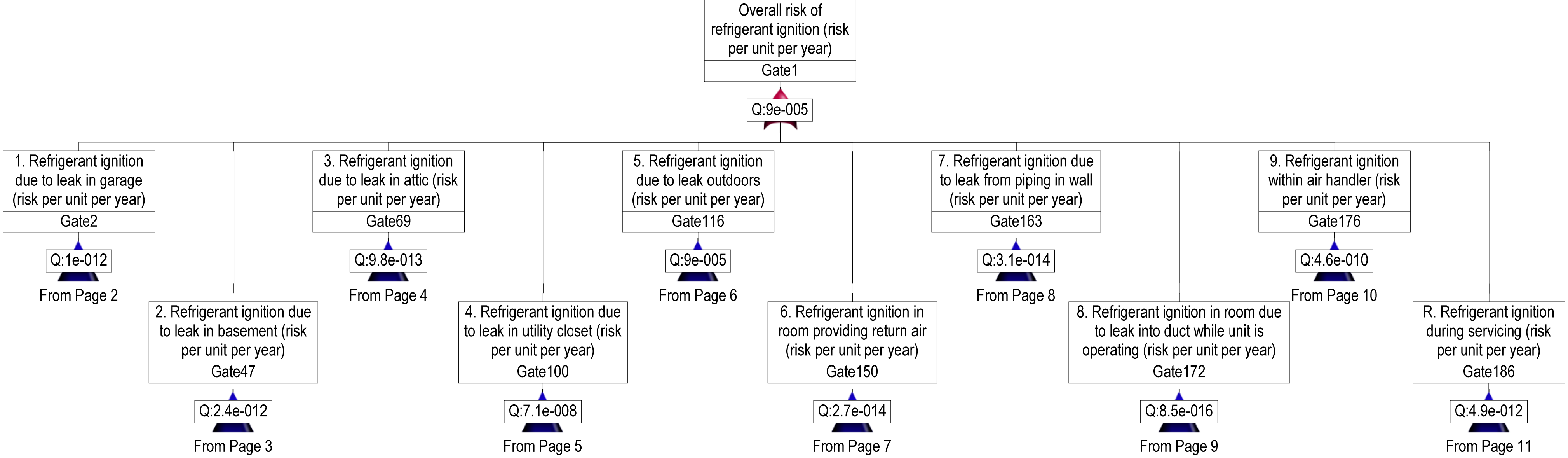
Event	Description	R-1234yf Value	R-1234ze Value	R32 Value	Remarks	Fault Tree
215	Deliberately vent to atmosphere	0.01	0.01	0.01	Goetzler et al. used 0.05, based on discouraging effect of training and regulations. In the prior analysis, the issue was regulatory compliance. Now it will be safety related so the probability of venting will be lower. Price will also encourage proper recovery.	R
216	Refrigerant concentration in flammable range (service scenario)	1.0	0.2	1.0	Assume that the refrigerant is in the flammable range at some location if a release occurs during repair for R-1234yf and R-32. However for R-1234-ze which is not flammable at ambient temperatures, the value is substantially less. Only near an operating furnace will such temperatures be reachable and such temperatures will not always occur.	R
219	Service person smokes during repair and uses a match to light cigarette	0.01	0.01	0.01	Goetzler et al. used 0.05 but the value should now be lower due to the higher cost of cigarettes, less tolerance of smoking in customer's homes and recognition of refrigerant flammability. The value is likely still high.	R
220	Match struck at relevant time (service)	7.0E-03	7.0E-03	7.0E-03	A match takes 5 seconds to strike and light a cigarette. A cigarette takes about 5 minutes to smoke. For a 30 minute service call and assuming the worker smokes continuously during the repair, the fraction of time the match is lit during service is 0.014 (0.083 minutes per match x 5 times/30 minutes). This assumes the cigarette itself cannot ignite the refrigerant (this has been demonstrated for R-1234yf by DuPont and Honeywell). A worker will not smoke continuously during the repair as they need both hands free and the cigarette may get in the way of some tasks. The value was therefore reduced by a factor of 2 to 0.007.	R
221	Match struck at relevant place (service)	1.0E-03	1.0E-03	1.0E-03	Goetzler et al. assumed that the service person will spend most of their time in proximity to the leak but that they will likely be standing to smoke and the leaked refrigerant will not rise upwards being slightly heavier than air. However, an element of human error is involved here because individuals will have to ignore their training if they are to strike a match near the unit.	R
230	Service person routinely uses torch to test for leaks	1.0E-04	1.0E-04	1.0E-04	Goetzler et al. used 0.05 but the value should now be much lower. Flame halide detectors are rarely used today, modern equipment that would not ignite refrigerant are available and inexpensive.	R
231	Serviceman believes refrigerant is non-flammable	1.0E-04	1.0E-04	1.0E-04	1E-3 is a typical value for human error related events but a value 10 times lower appears appropriate because the repair person would have to ignore obvious markings and disregard their training, a benefit not found in the typical individual on whom the 1E-3 value is based.	R
232	Fraction of service calls involving a moderate or large leak	0.01	0.01	0.01	Goetzler et al. based on ADL proprietary data.	R
393	Case around fan motor does not prevent flame propagation to rest of refrigerant	1.0E-05	1.0E-05	1.0E-05	Assumes the case is poorly designed or defective (not a part subject to repair). Based on standard probabilities for product design faults.	5
396	Control system spark occurs at relevant time	3.0E-04	3.0E-04	3.0E-04	Assume there are 2 power cycles per hour, and thus 48 per day, or 17,520 per year. Further assume the duration of any arc is ½ second. Thus 8760 seconds of potential arc time per year divided by the number of seconds per year (3.15E7) is 3E-4.	5
397	Fan motor spark occurs at relevant time	3.0E-04	3.0E-04	3.0E-04	Assume there are 2 power cycles per hour, and thus 48 per day or 17,520 per year. Further assume the duration of any arc is ½ second. Thus 8760 seconds of potential arc time per year divided by the number of seconds per year (3.15E7) is 3E-4.	5
400	Service person recharges leak prior to looking for leak with flammable refrigerant	0.3	0.3	0.3	If the leak is large enough, enough refrigerant will have leaked out prior to the service call such that a flammable concentration cannot form. Only if the system is recharged with flammable refrigerant before looking for the leak will there be a risk of ignition. Group consensus value.	R
401	Large leak is not detected by other means	0.1	0.1	0.1	Even if the service person normally uses a propane torch to test for leaks he/she may use other methods first. Group consensus value.	R

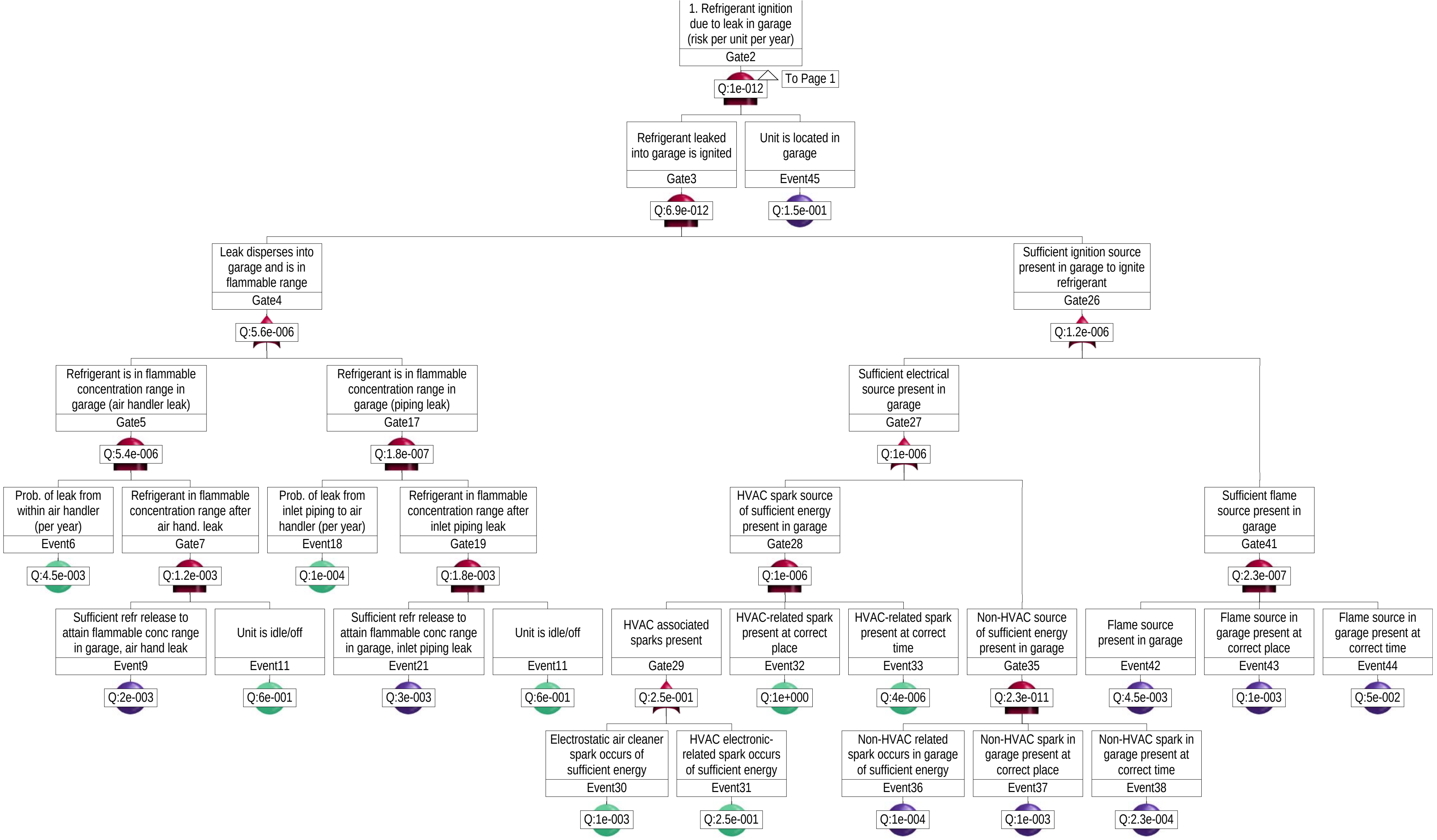
Table C.1 Inputs Probabilities for Fault Trees

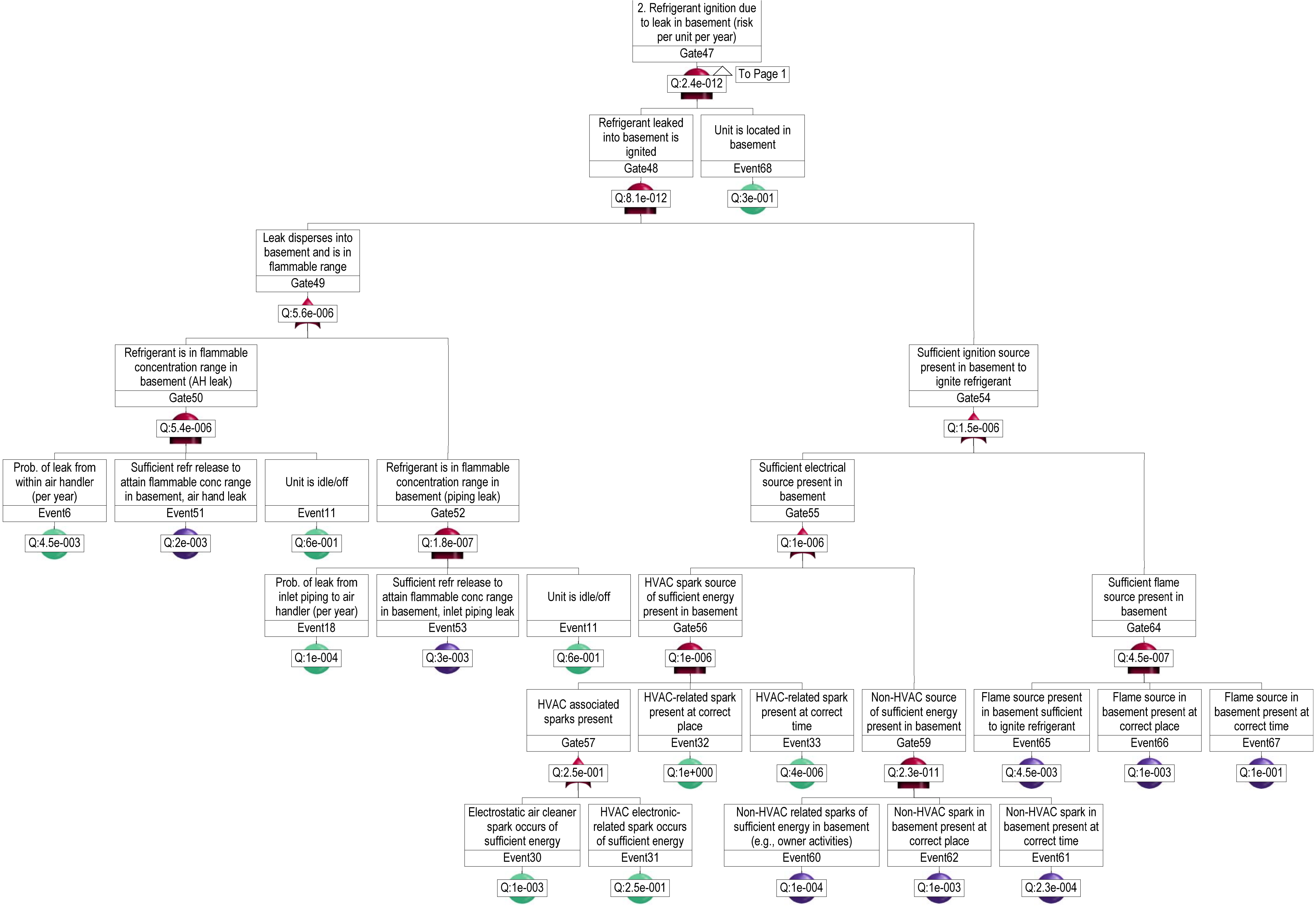
Event	Description	R-1234yf Value	R-1234ze Value	R32 Value	Remarks	Fault Tree
402	Flammable concentration forms in return air room as refrigerant is blown through the ducts into the room	1.0E-05	1.0E-05	1.0E-05	CFD modeling suggests a negligible risk. Even when airflow was negligible, the refrigerants rapidly disbursed into room air and formed non-flammable concentrations. The only room where flammable concentrations were observed was the utility closet and a portion of the adjacent kitchen (only at the 6" height). However, with active air flow refrigerant would likely be pushed into adjoining rooms and rapidly mixed. A value of 1E-5 was used for all refrigerants.	8
423	Ignition source occurs at same place as leak	0.2	0.2	0.2	It cannot be assumed that the short will occur in a portion of the wall where the refrigerant piping is located or where the refrigerant may accumulate to a level that reaches the LFL. Insulation or framing may limit dispersion of refrigerant inside the wall. A value of 0.2 is used.	
900	Ambient temperature sufficient for 1234ze to be flammable (garage/attic)	NA	0.3	NA	A value of 0.3 is used for the 3 summer months. In some regions (e.g., the Northwest) temperatures will rarely if ever get above 86 degrees F, in other regions (e.g., the Northeast and Great Lakes areas) temperatures above 86s will not occur consistently during the summer, and in other regions (e.g., the desert Southwest, Southern Texas) temperatures may be above 86 for more than 3 months. Therefore a value of 0.3 is reasonable for a national	1,3
901	Ambient temperature sufficient for 1234ze to be flammable (basement)	NA	0.03	NA	Basements are typically cooler than the rest of the home. Only during periods of consistently very hot weather would the temperature in the basement get close to 86 degrees. Note that most homes in very hot climates (e.g., the desert Southwest) do not have basements.	2
903	Ambient temperature sufficient for 1234ze to be flammable (utility closet)	NA	0.01	NA	It is unlikely that temperatures inside the house (including the utility closet) would exceed 90°F (32°C) in any season except the summer. Even in this period, the house will normally be cooled and only in the event of the AC/heat pump system failure would the indoor temperature eventually get this high. However, some time will be required for the indoor temperature to rise. Thus the system would have to stop working for a period of at least a few hours and THEN experience a refrigerant leak, an unlikely occurrence. If the release of the refrigerant is the cause the of temperature increase, the refrigerant will likely have dispersed by the time the temperature in the utility closet increases such to the extent that 1234ze becomes flammable. A more likely scenario would be an increase in temperature in the utility closet due to improper venting of a clothes dryer or other heating appliance. This could cause localized spots of high temperature (but again even these might not exceed 90F in cooler months). A value of 0.01 is used but may be overly conservative given that the typical human error probability is 1E-3.	4
904	Temperature in outdoor unit interior sufficient for 1234ze to be flammable	NA	1.0	NA	The outdoor unit has a fairly small volume and if the refrigerant is not dispersed by wind (Event 132) it is likely to reach some portion inside the unit where the temperature is sufficient for 1234ze to be flammable.	5
905	Temperature sufficient for R-1234ze to be flammable (feed through plug)	NA	1.0	NA	If the feed through plug fails, the local temperature around the plug will be sufficient for R-1234ze to be flammable.	5
906	Sufficient temperature in room for R-1234ze to be flammable	NA	1.0E-04	NA	It is unlikely that temperatures inside the house would exceed 90°F (32°C) in any season except the summer. Even in this period, the house will normally be cooled and only in the event of the AC/heat pump system failure would the indoor temperature eventually get this high. However, some time will be required for the indoor temperature to rise. Thus the system would have to stop working for a period of at least a few hours and THEN experience a refrigerant leak, an extremely unlikely occurrence. If the release of the refrigerant is the cause the of temperature increase, the refrigerant will likely have dispersed by the time the temperature in the utility closet increases such to the extent that 1234ze becomes flammable. If the AC system is not working and temperature are getting up towards 90F, it is unlikely the residents will use appliances or other devices which would further increase the temperature. A low value of 0.0001 is used.	6,8

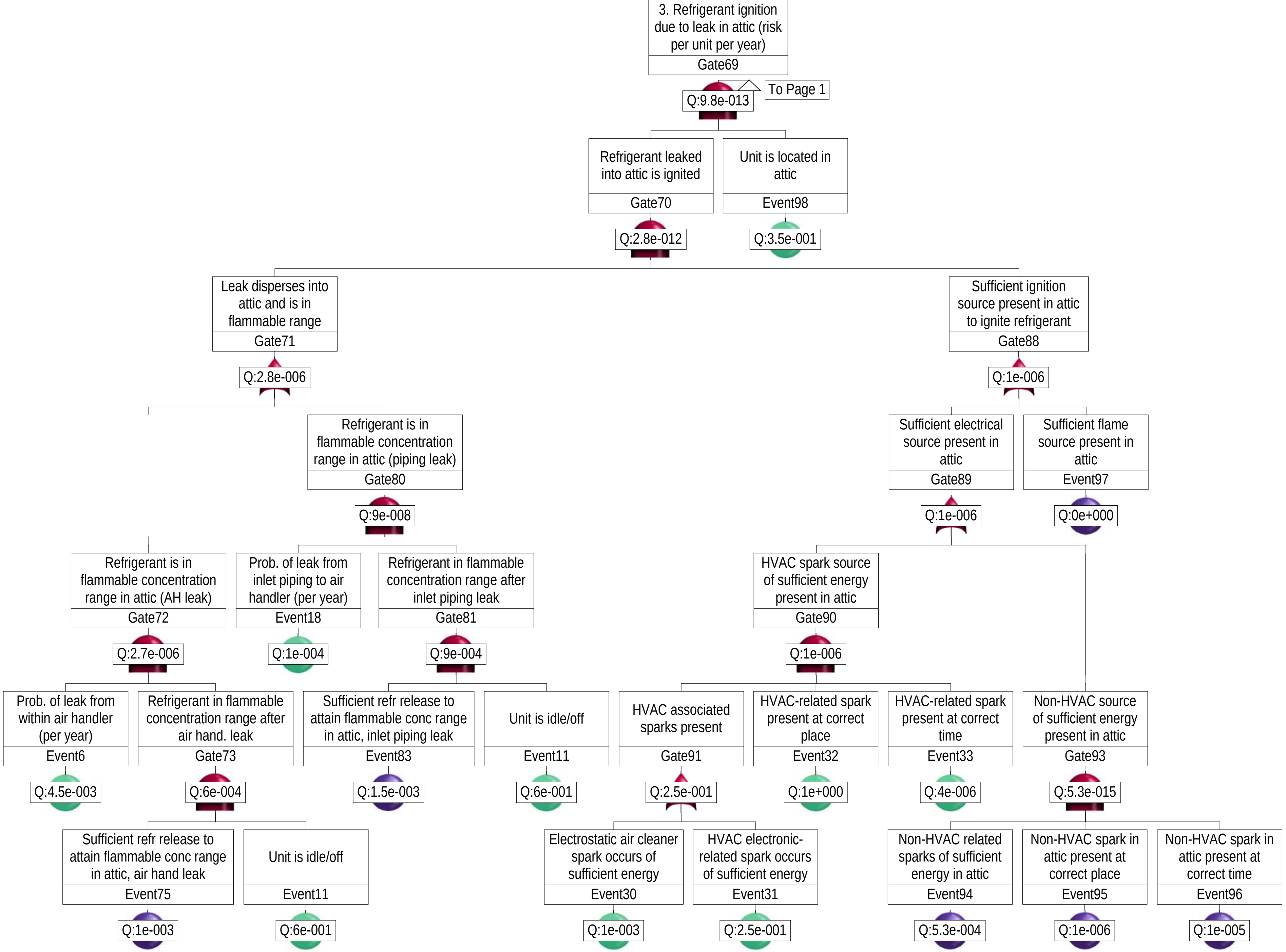
Table C.1 Inputs Probabilities for Fault Trees

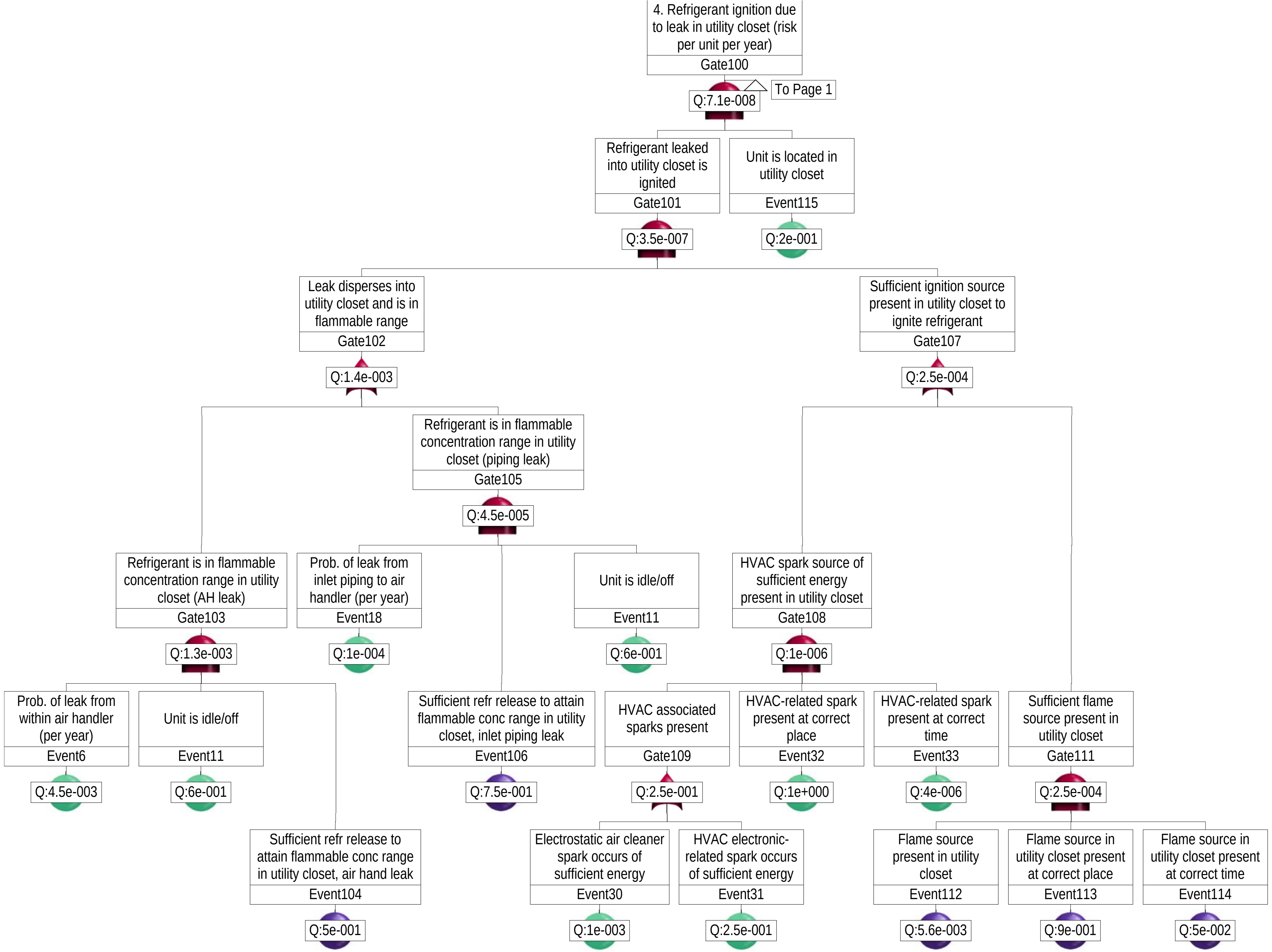
Event	Description	R-1234yf Value	R-1234ze Value	R32 Value	Remarks	Fault Tree
907	Sufficient temperature in walls for R-1234ze to be flammable	NA	0.04	NA	Walls of the house, if on the exterior and exposed to the sun could be sufficient warm for R-1234ze to be flammable on hot summer days. Not all walls are exterior nor are all walls always exposed to the sun. A value of 0.04 (0.3 for summer months x 0.5 for the wall in question being interior or exterior x 0.25 for the wall in question facing the sun)	7
908	Sufficient temperature for R-1234ze to be flammable in air handler	NA	1.0	NA	If the heat elements are on (Event 184) the temperature in the air handler will be sufficient for R-1234ze to be flammable.	9
909	Ambient temperature is sufficient for R-1234ze to be flammable (indoor repair)	NA	0.3	NA	The same value is used as for the attic and garage repair situation, reflecting the time period when ambient outdoor temperatures might be in the 86 degree range. The value therefore overestimates the probability for units with the interior portion located in the utility closet and basement.	R
910	Ambient temperature is sufficient for R-1234ze to be flammable (outdoor repair)	NA	0.3	NA	The same value is used as for the attic and garage repair situation, reflecting the time period when ambient outdoor temperatures might be in the 86 degree range.	R

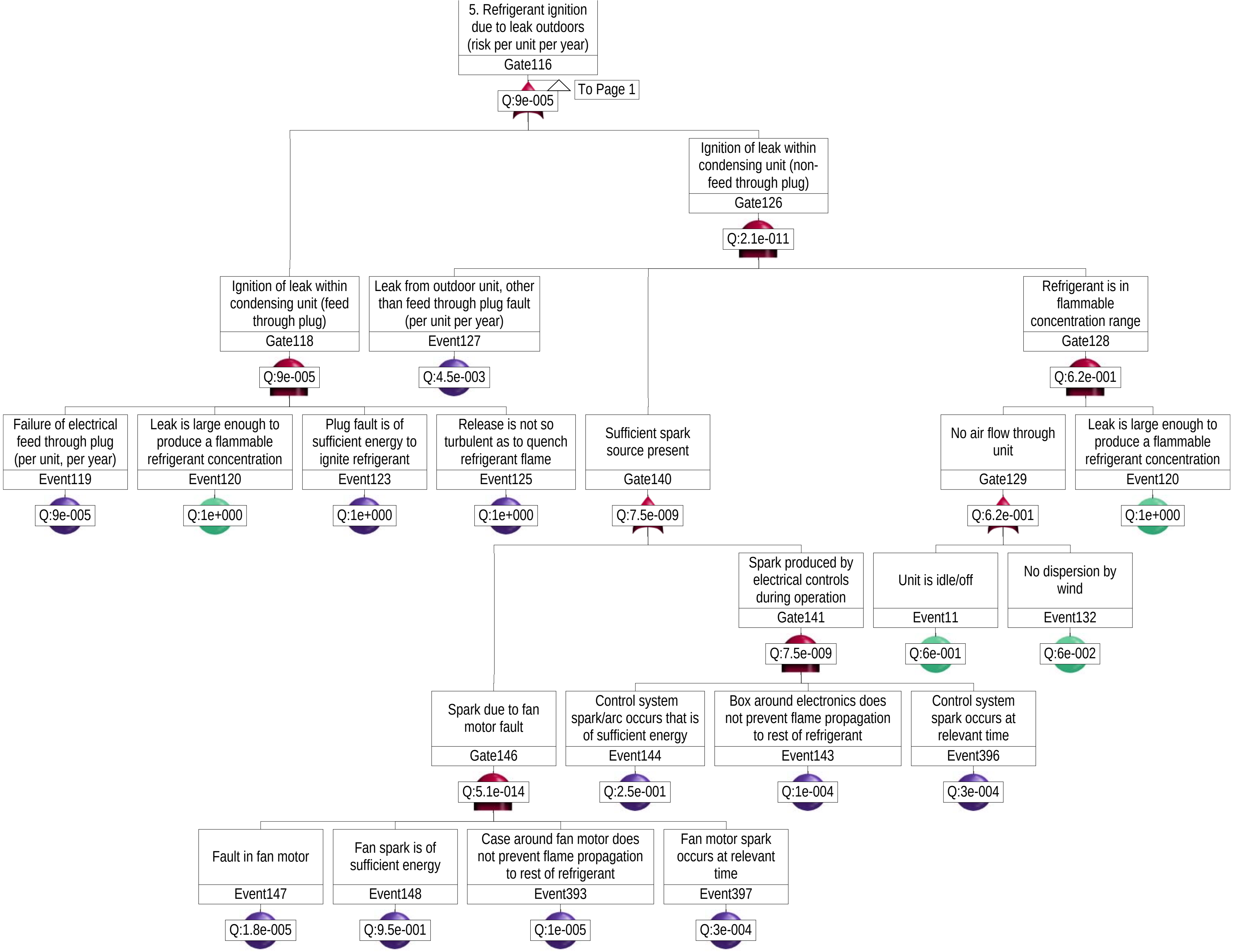

Overall risk of refrigerant ignition (risk per unit per year)
Gate1
Q:9e-005
1. Refrigerant ignition due to leak in garage (risk per unit per year)
Gate2
Q:1e-012
From Page 2
2. Refrigerant ignition due to leak in basement (risk per unit per year)
Gate47
Q:2.4e-012
From Page 3
3. Refrigerant ignition due to leak in attic (risk per unit per year)
Gate69
Q:9.8e-013
From Page 4
4. Refrigerant ignition due to leak in utility closet (risk per unit per year)
Gate100
Q:7.1e-008
From Page 5
5. Refrigerant ignition due to leak outdoors (risk per unit per year)
Gate116
Q:9e-005
From Page 6
6. Refrigerant ignition in room providing return air (risk per unit per year)
Gate150
Q:2.7e-014
From Page 7
7. Refrigerant ignition due to leak from piping in wall (risk per unit per year)
Gate163
Q:3.1e-014
From Page 8
8. Refrigerant ignition in room due to leak into duct while unit is operating (risk per unit per year)
Gate172
Q:8.5e-016
From Page 9
9. Refrigerant ignition within air handler (risk per unit per year)
Gate176
Q:4.6e-010
From Page 10
R. Refrigerant ignition during servicing (risk per unit per year)
Gate186
Q:4.9e-012
From Page 11

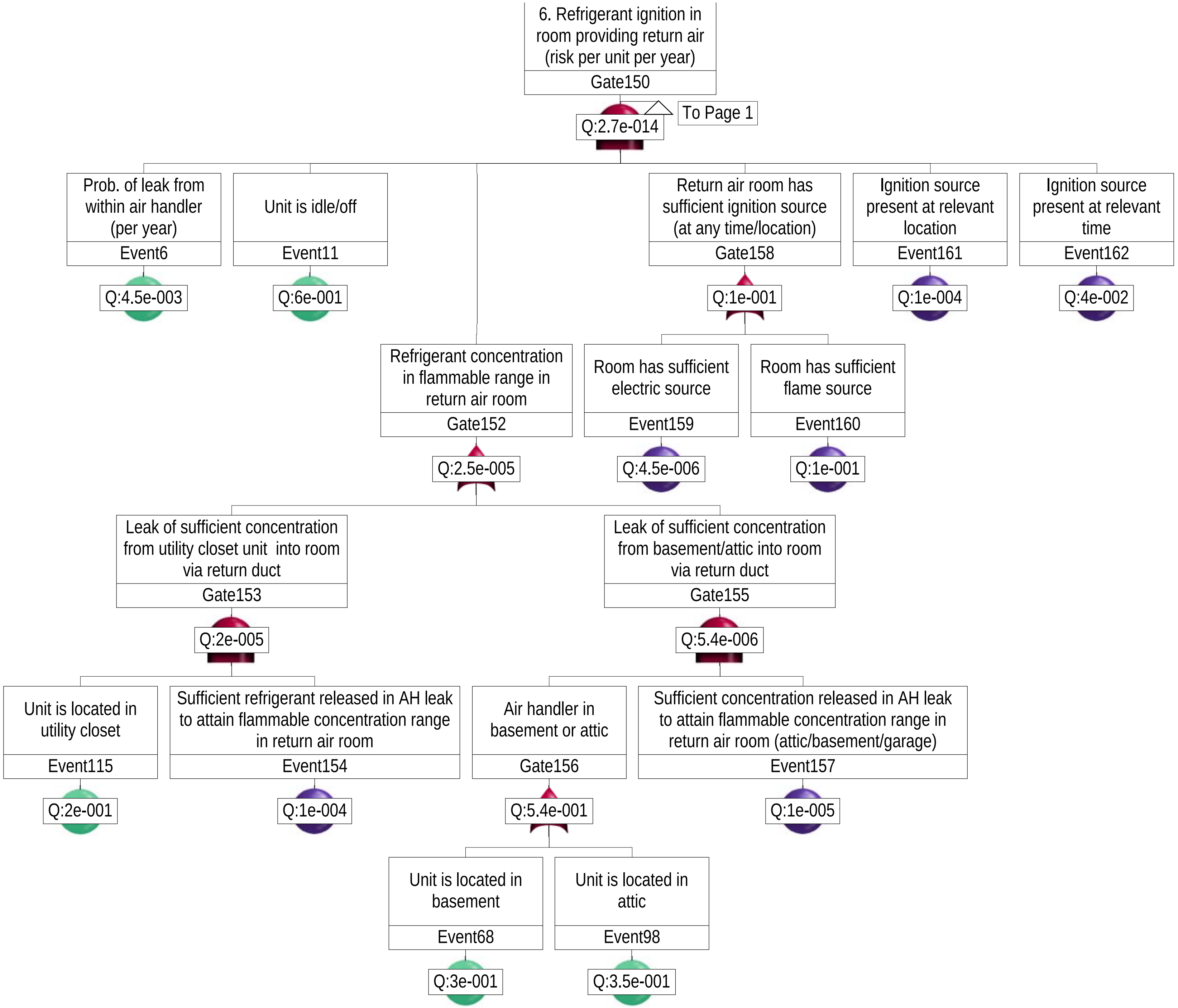

1. Refrigerant ignition due to leak in garage (risk per unit per year)
Gate2
Q:1e-012
To Page 1
Refrigerant leaked into garage is ignited
Gate3
Q:6.9e-012
Unit is located in garage
Event45
Q:1.5e-001
Leak disperses into garage and is in flammable range
Gate4
Q:5.6e-006
Sufficient ignition source present in garage to ignite refrigerant
Gate26
Q:1.2e-006
Refrigerant is in flammable concentration range in garage (air handler leak)
Gate5
Q:5.4e-006
Refrigerant is in flammable concentration range in garage (piping leak)
Gate17
Q:1.8e-007
Sufficient electrical source present in garage
Gate27
Q:1e-006
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Refrigerant in flammable concentration range after air hand. leak
Gate7
Q:1.2e-003
Prob. of leak from inlet piping to air handler (per year)
Event18
Q:1e-004
Refrigerant in flammable concentration range after inlet piping leak
Gate19
Q:1.8e-003
HVAC spark source of sufficient energy present in garage
Gate28
Q:1e-006
Sufficient flame source present in garage
Gate41
Q:2.3e-007
Sufficient refr release to attain flammable conc range in garage, air hand leak
Event9
Q:2e-003
Unit is idle/off
Event11
Q:6e-001
Sufficient refr release to attain flammable conc range in garage, inlet piping leak
Event21
Q:3e-003
Unit is idle/off
Event11
Q:6e-001
HVAC associated sparks present
Gate29
Q:2.5e-001
HVAC-related spark present at correct place
Event32
Q:1e+000
HVAC-related spark present at correct time
Event33
Q:4e-006
Non-HVAC source of sufficient energy present in garage
Gate35
Q:2.3e-011
Flame source present in garage
Event42
Q:4.5e-003
Flame source in garage present at correct place
Event43
Q:1e-003
Flame source in garage present at correct time
Event44
Q:5e-002
Electrostatic air cleaner spark occurs of sufficient energy
Event30
Q:1e-003
HVAC electronic-related spark occurs of sufficient energy
Event31
Q:2.5e-001
Non-HVAC related spark occurs in garage of sufficient energy
Event36
Q:1e-004
Non-HVAC spark in garage present at correct place
Event37
Q:1e-003
Non-HVAC spark in garage present at correct time
Event38
Q:2.3e-004

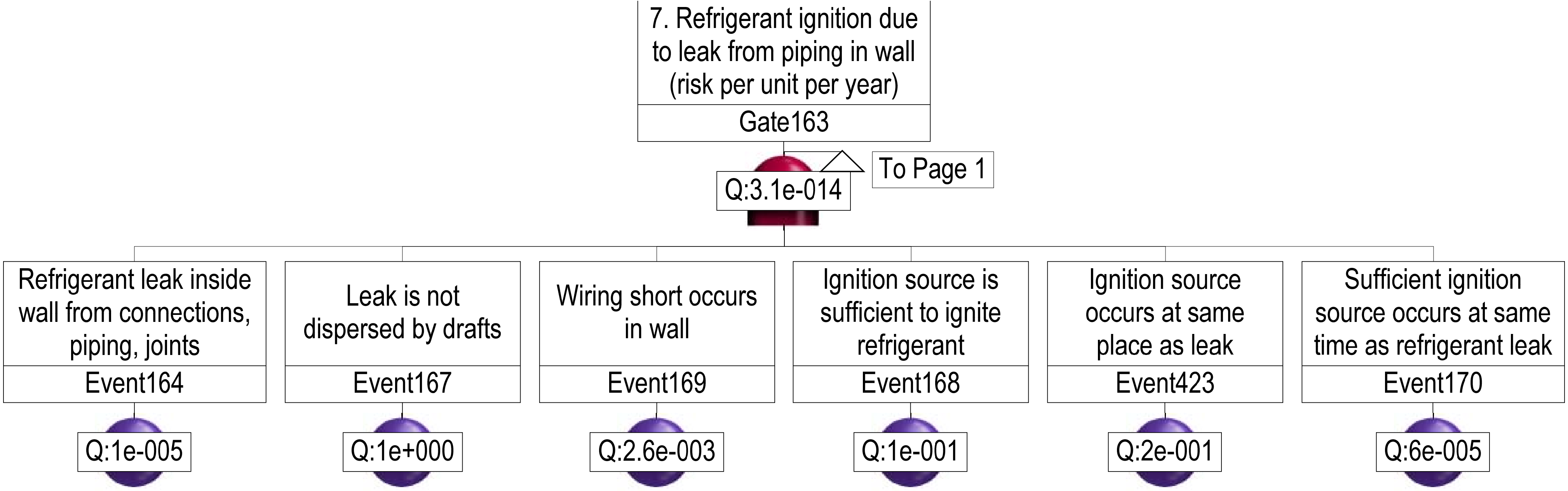

2. Refrigerant ignition due to leak in basement (risk per unit per year)
Gate47
Q:2.4e-012
To Page 1
Refrigerant leaked into basement is ignited
Gate48
Q:8.1e-012
Unit is located in basement
Event68
Q:3e-001
Leak disperses into basement and is in flammable range
Gate49
Q:5.6e-006
Refrigerant is in flammable concentration range in basement (AH leak)
Gate50
Q:5.4e-006
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Sufficient refr release to attain flammable conc range in basement, air hand leak
Event51
Q:2e-003
Unit is idle/off
Event11
Q:6e-001
Refrigerant is in flammable concentration range in basement (piping leak)
Gate52
Q:1.8e-007
Prob. of leak from inlet piping to air handler (per year)
Event18
Q:1e-004
Sufficient refr release to attain flammable conc range in basement, inlet piping leak
Event53
Q:3e-003
Unit is idle/off
Event11
Q:6e-001
Sufficient ignition source present in basement to ignite refrigerant
Gate54
Q:1.5e-006
Sufficient electrical source present in basement
Gate55
Q:1e-006
HVAC spark source of sufficient energy present in basement
Gate56
Q:1e-006
HVAC associated sparks present
Gate57
Q:2.5e-001
Electrostatic air cleaner spark occurs of sufficient energy
Event30
Q:1e-003
HVAC electronic-related spark occurs of sufficient energy
Event31
Q:2.5e-001
HVAC-related spark present at correct place
Event32
Q:1e+000
HVAC-related spark present at correct time
Event33
Q:4e-006
Non-HVAC source of sufficient energy present in basement
Gate59
Q:2.3e-011
Non-HVAC related sparks of sufficient energy in basement (e.g., owner activities)
Event60
Q:1e-004
Non-HVAC spark in basement present at correct place
Event62
Q:1e-003
Non-HVAC spark in basement present at correct time
Event61
Q:2.3e-004
Sufficient flame source present in basement
Gate64
Q:4.5e-007
Flame source present in basement sufficient to ignite refrigerant
Event65
Q:4.5e-003
Flame source in basement present at correct place
Event66
Q:1e-003
Flame source in basement present at correct time
Event67
Q:1e-001

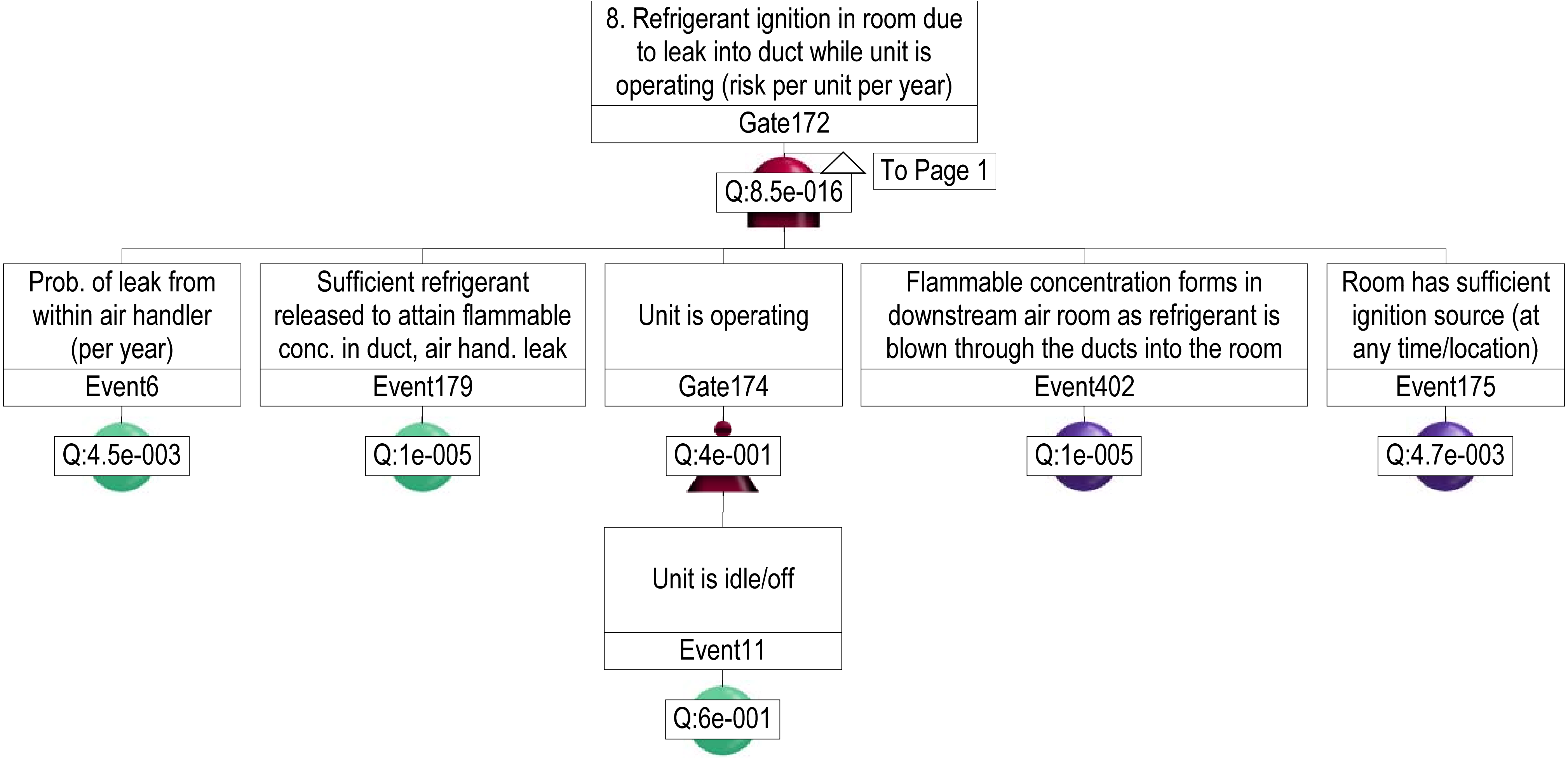

3. Refrigerant ignition due to leak in attic (risk per unit per year)
Gate69
Q:9.8e-013
To Page 1
Refrigerant leaked into attic is ignited
Gate70
Q:2.8e-012
Unit is located in attic
Event98
Q:3.5e-001
Leak disperses into attic and is in flammable range
Gate71
Q:2.8e-006
Sufficient ignition source present in attic to ignite refrigerant
Gate88
Q:1e-006
Refrigerant is in flammable concentration range in attic (piping leak)
Gate80
Q:9e-008
Sufficient electrical source present in attic
Gate89
Q:1e-006
Sufficient flame source present in attic
Event97
Q:0e+000
Refrigerant is in flammable concentration range in attic (AH leak)
Gate72
Q:2.7e-006
Prob. of leak from inlet piping to air handler (per year)
Event18
Q:1e-004
Refrigerant in flammable concentration range after inlet piping leak
Gate81
Q:9e-004
HVAC spark source of sufficient energy present in attic
Gate90
Q:1e-006
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Refrigerant in flammable concentration range after air hand. leak
Gate73
Q:6e-004
Sufficient refr release to attain flammable conc range in attic, inlet piping leak
Event83
Q:1.5e-003
Unit is idle/off
Event11
Q:6e-001
HVAC associated sparks present
Gate91
Q:2.5e-001
HVAC-related spark present at correct place
Event32
Q:1e+000
HVAC-related spark present at correct time
Event33
Q:4e-006
Non-HVAC source of sufficient energy present in attic
Gate93
Q:5.3e-015
Sufficient refr release to attain flammable conc range in attic, air hand leak
Event75
Q:1e-003
Unit is idle/off
Event11
Q:6e-001
Electrostatic air cleaner spark occurs of sufficient energy
Event30
Q:1e-003
HVAC electronic-related spark occurs of sufficient energy
Event31
Q:2.5e-001
Non-HVAC related sparks of sufficient energy in attic
Event94
Q:5.3e-004
Non-HVAC spark in attic present at correct place
Event95
Q:1e-006
Non-HVAC spark in attic present at correct time
Event96
Q:1e-005

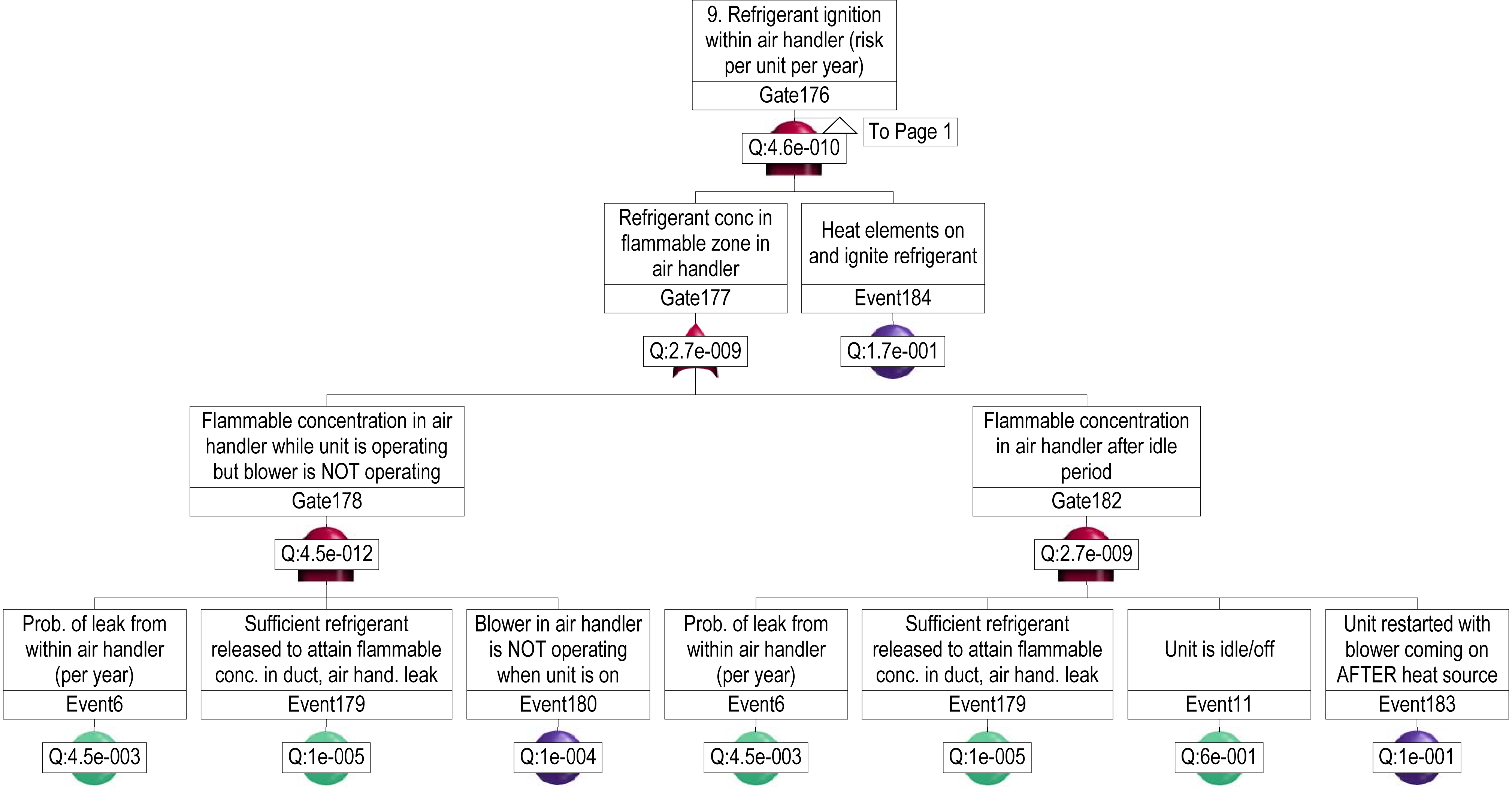

4. Refrigerant ignition due to leak in utility closet (risk per unit per year)
Gate100
Q:7.1e-008
To Page 1
Refrigerant leaked into utility closet is ignited
Gate101
Q:3.5e-007
Unit is located in utility closet
Event115
Q:2e-001
Leak disperses into utility closet and is in flammable range
Gate102
Q:1.4e-003
Sufficient ignition source present in utility closet to ignite refrigerant
Gate107
Q:2.5e-004
Refrigerant is in flammable concentration range in utility closet (piping leak)
Gate105
Q:4.5e-005
Refrigerant is in flammable concentration range in utility closet (AH leak)
Gate103
Q:1.3e-003
Prob. of leak from inlet piping to air handler (per year)
Event18
Q:1e-004
Unit is idle/off
Event11
Q:6e-001
HVAC spark source of sufficient energy present in utility closet
Gate108
Q:1e-006
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Unit is idle/off
Event11
Q:6e-001
Sufficient refr release to attain flammable conc range in utility closet, inlet piping leak
Event106
Q:7.5e-001
HVAC associated sparks present
Gate109
Q:2.5e-001
HVAC-related spark present at correct place
Event32
Q:1e+000
HVAC-related spark present at correct time
Event33
Q:4e-006
Sufficient flame source present in utility closet
Gate111
Q:2.5e-004
Sufficient refr release to attain flammable conc range in utility closet, air hand leak
Event104
Q:5e-001
Electrostatic air cleaner spark occurs of sufficient energy
Event30
Q:1e-003
HVAC electronic-related spark occurs of sufficient energy
Event31
Q:2.5e-001
Flame source present in utility closet
Event112
Q:5.6e-003
Flame source in utility closet present at correct place
Event113
Q:9e-001
Flame source in utility closet present at correct time
Event114
Q:5e-002

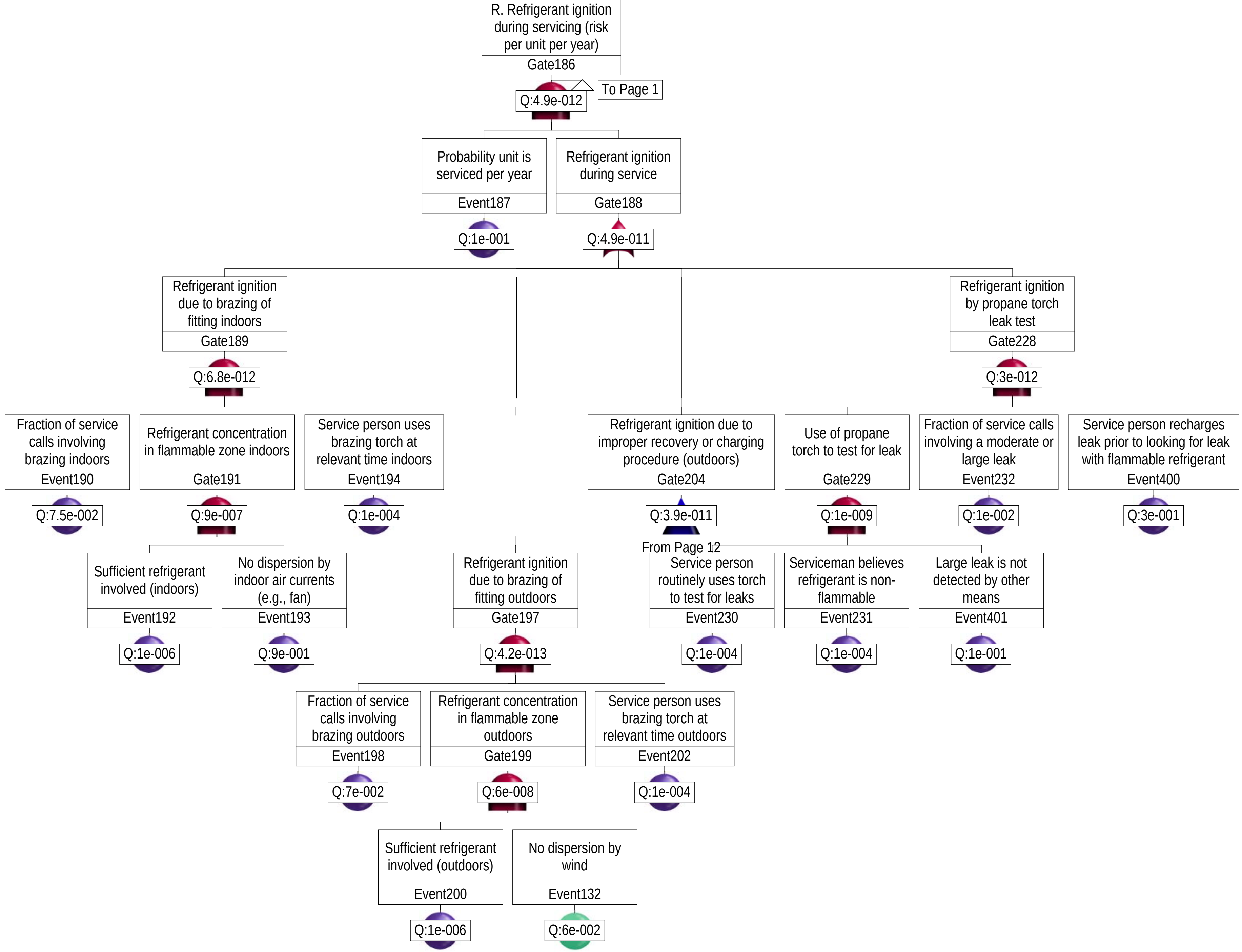

5. Refrigerant ignition due to leak outdoors (risk per unit per year)
Gate116
Q:9e-005
To Page 1
Ignition of leak within condensing unit (non-feed through plug)
Gate126
Q:2.1e-011
Ignition of leak within condensing unit (feed through plug)
Gate118
Q:9e-005
Leak from outdoor unit, other than feed through plug fault (per unit per year)
Event127
Q:4.5e-003
Refrigerant is in flammable concentration range
Gate128
Q:6.2e-001
Failure of electrical feed through plug (per unit, per year)
Event119
Q:9e-005
Leak is large enough to produce a flammable refrigerant concentration
Event120
Q:1e+000
Plug fault is of sufficient energy to ignite refrigerant
Event123
Q:1e+000
Release is not so turbulent as to quench refrigerant flame
Event125
Q:1e+000
Sufficient spark source present
Gate140
Q:7.5e-009
No air flow through unit
Gate129
Q:6.2e-001
Leak is large enough to produce a flammable refrigerant concentration
Event120
Q:1e+000
Spark produced by electrical controls during operation
Gate141
Q:7.5e-009
Unit is idle/off
Event11
Q:6e-001
No dispersion by wind
Event132
Q:6e-002
Spark due to fan motor fault
Gate146
Q:5.1e-014
Control system spark/arc occurs that is of sufficient energy
Event144
Q:2.5e-001
Box around electronics does not prevent flame propagation to rest of refrigerant
Event143
Q:1e-004
Control system spark occurs at relevant time
Event396
Q:3e-004
Fault in fan motor
Event147
Q:1.8e-005
Fan spark is of sufficient energy
Event148
Q:9.5e-001
Case around fan motor does not prevent flame propagation to rest of refrigerant
Event393
Q:1e-005
Fan motor spark occurs at relevant time
Event397
Q:3e-004

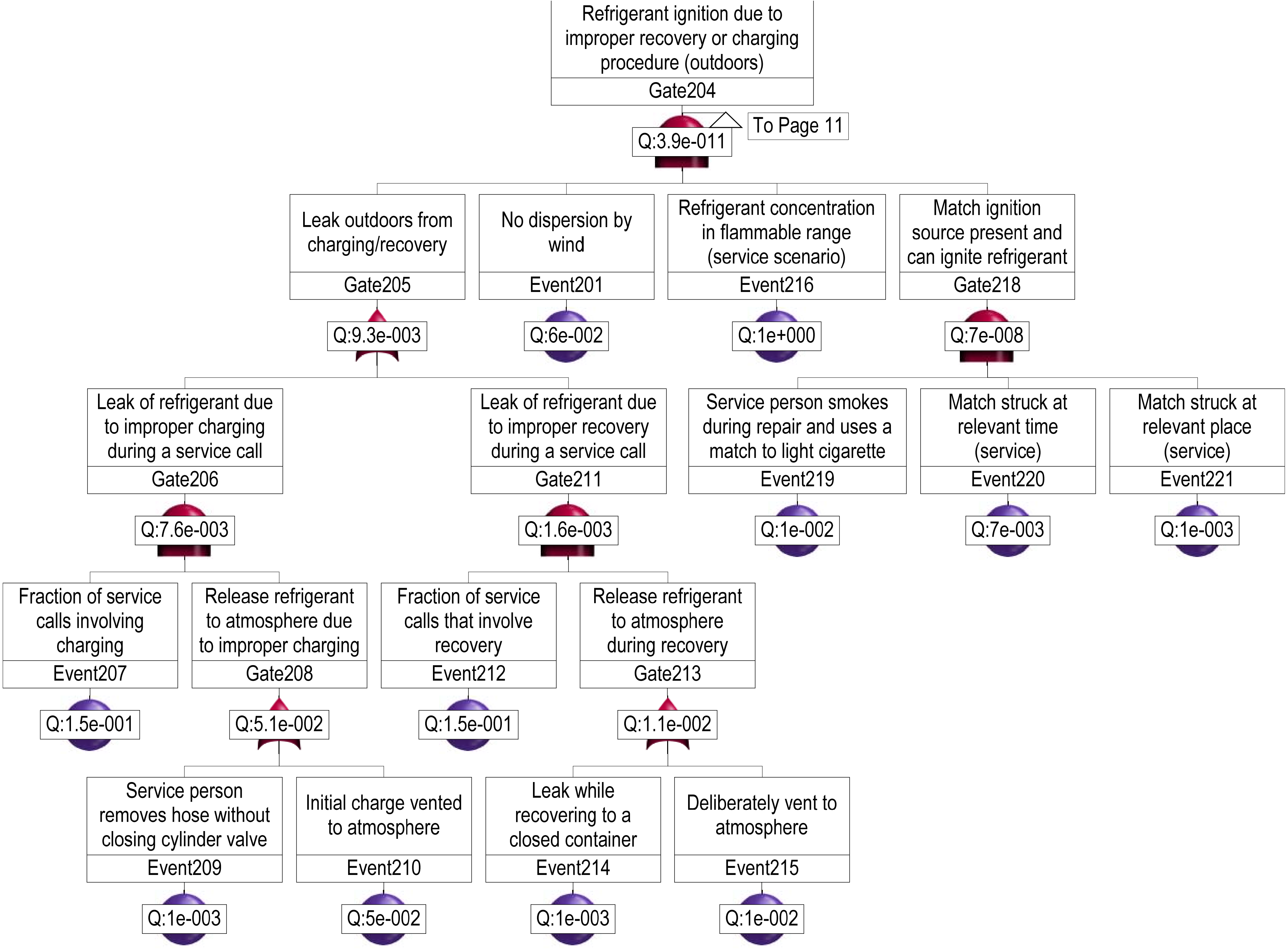

6. Refrigerant ignition in room providing return air (risk per unit per year)
Gate150
Q:2.7e-014
To Page 1
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Unit is idle/off
Event11
Q:6e-001
Return air room has sufficient ignition source (at any time/location)
Gate158
Q:1e-001
Ignition source present at relevant location
Event161
Q:1e-004
Ignition source present at relevant time
Event162
Q:4e-002
Refrigerant concentration in flammable range in return air room
Gate152
Q:2.5e-005
Room has sufficient electric source
Event159
Q:4.5e-006
Room has sufficient flame source
Event160
Q:1e-001
Leak of sufficient concentration from utility closet unit into room via return duct
Gate153
Q:2e-005
Leak of sufficient concentration from basement/attic into room via return duct
Gate155
Q:5.4e-006
Unit is located in utility closet
Event115
Q:2e-001
Sufficient refrigerant released in AH leak to attain flammable concentration range in return air room
Event154
Q:1e-004
Air handler in basement or attic
Gate156
Q:5.4e-001
Sufficient concentration released in AH leak to attain flammable concentration range in return air room (attic/basement/garage)
Event157
Q:1e-005
Unit is located in basement
Event68
Q:3e-001
Unit is located in attic
Event98
Q:3.5e-001

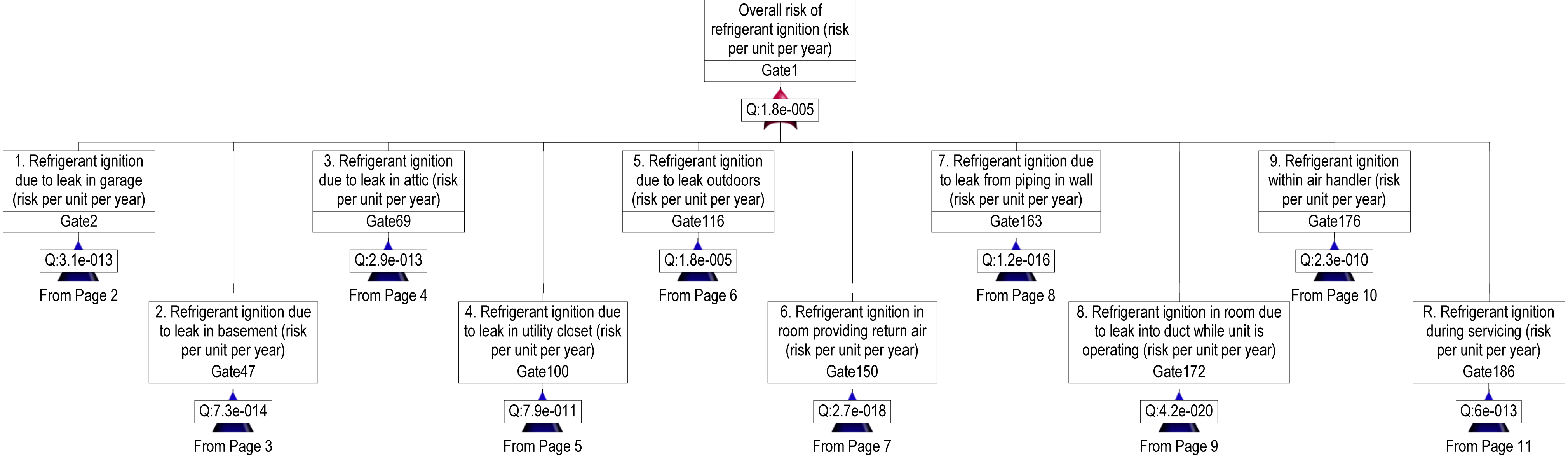

7. Refrigerant ignition due to leak from piping in wall (risk per unit per year)
Gate163
Q:3.1e-014
To Page 1
Refrigerant leak inside wall from connections, piping, joints
Event164
Q:1e-005
Leak is not dispersed by drafts
Event167
Q:1e+000
Wiring short occurs in wall
Event169
Q:2.6e-003
Ignition source is sufficient to ignite refrigerant
Event168
Q:1e-001
Ignition source occurs at same place as leak
Event423
Q:2e-001
Sufficient ignition source occurs at same time as refrigerant leak
Event170
Q:6e-005

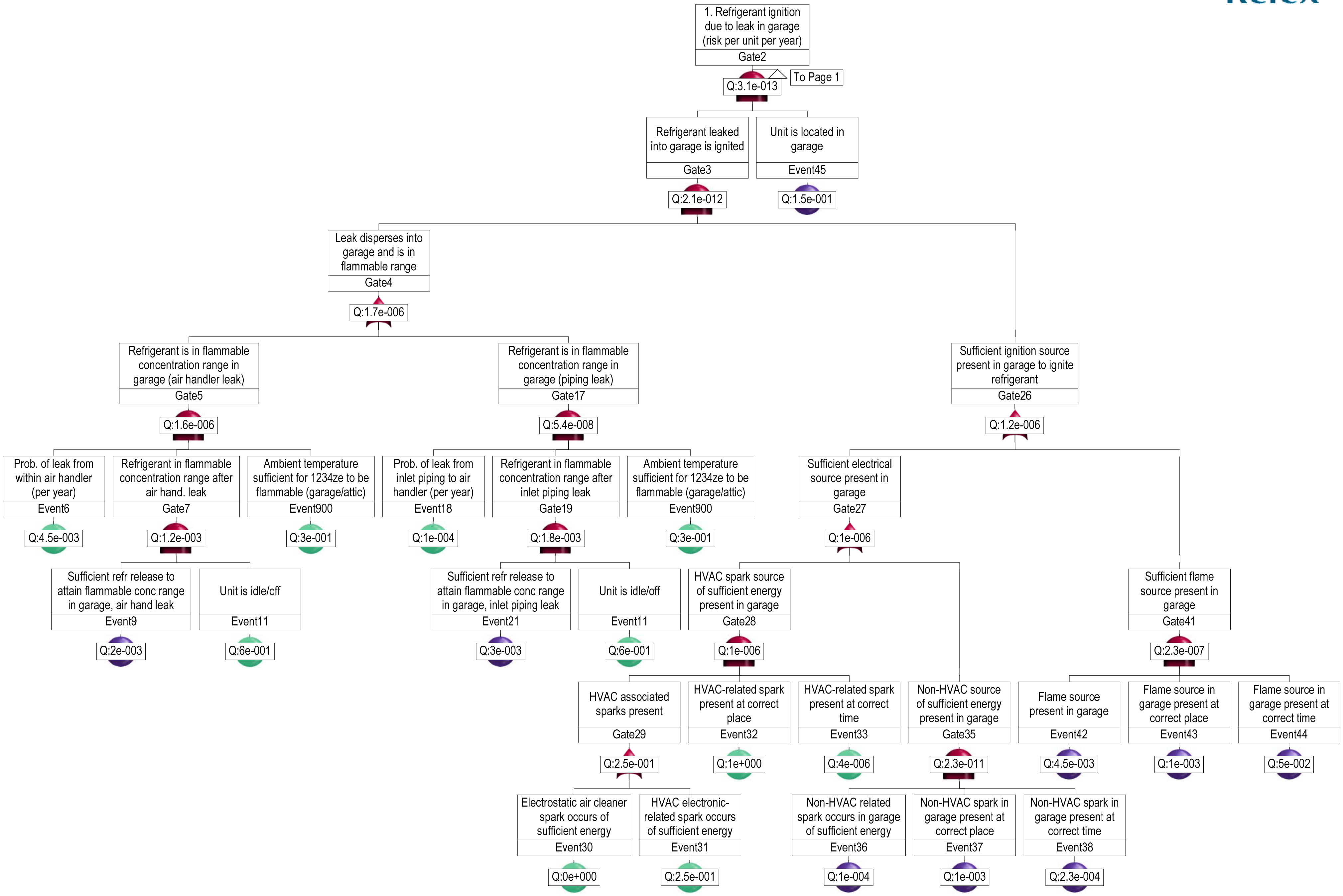

8. Refrigerant ignition in room due to leak into duct while unit is operating (risk per unit per year)
Gate172
Q:8.5e-016
To Page 1
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Sufficient refrigerant released to attain flammable conc. in duct, air hand. leak
Event179
Q:1e-005
Unit is operating
Gate174
Q:4e-001
Unit is idle/off
Event11
Q:6e-001
Flammable concentration forms in downstream air room as refrigerant is blown through the ducts into the room
Event402
Q:1e-005
Room has sufficient ignition source (at any time/location)
Event175
Q:4.7e-003

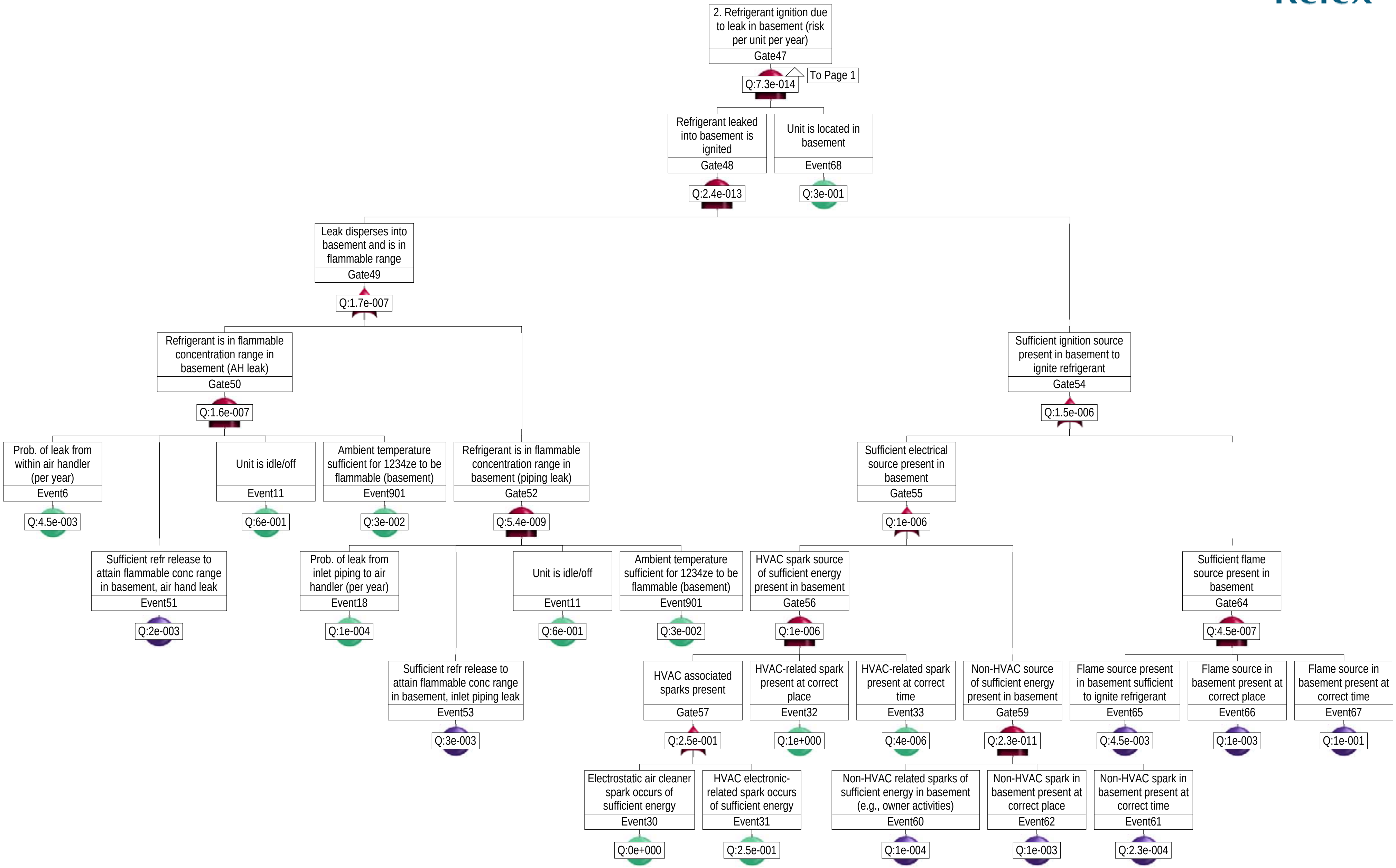

9. Refrigerant ignition within air handler (risk per unit per year)
Gate176
Q:4.6e-010
To Page 1
Refrigerant conc in flammable zone in air handler
Gate177
Q:2.7e-009
Heat elements on and ignite refrigerant
Event184
Q:1.7e-001
Flammable concentration in air handler while unit is operating but blower is NOT operating
Gate178
Q:4.5e-012
Flammable concentration in air handler after idle period
Gate182
Q:2.7e-009
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Sufficient refrigerant released to attain flammable conc. in duct, air hand. leak
Event179
Q:1e-005
Blower in air handler is NOT operating when unit is on
Event180
Q:1e-004
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Sufficient refrigerant released to attain flammable conc. in duct, air hand. leak
Event179
Q:1e-005
Unit is idle/off
Event11
Q:6e-001
Unit restarted with blower coming on AFTER heat source
Event183
Q:1e-001

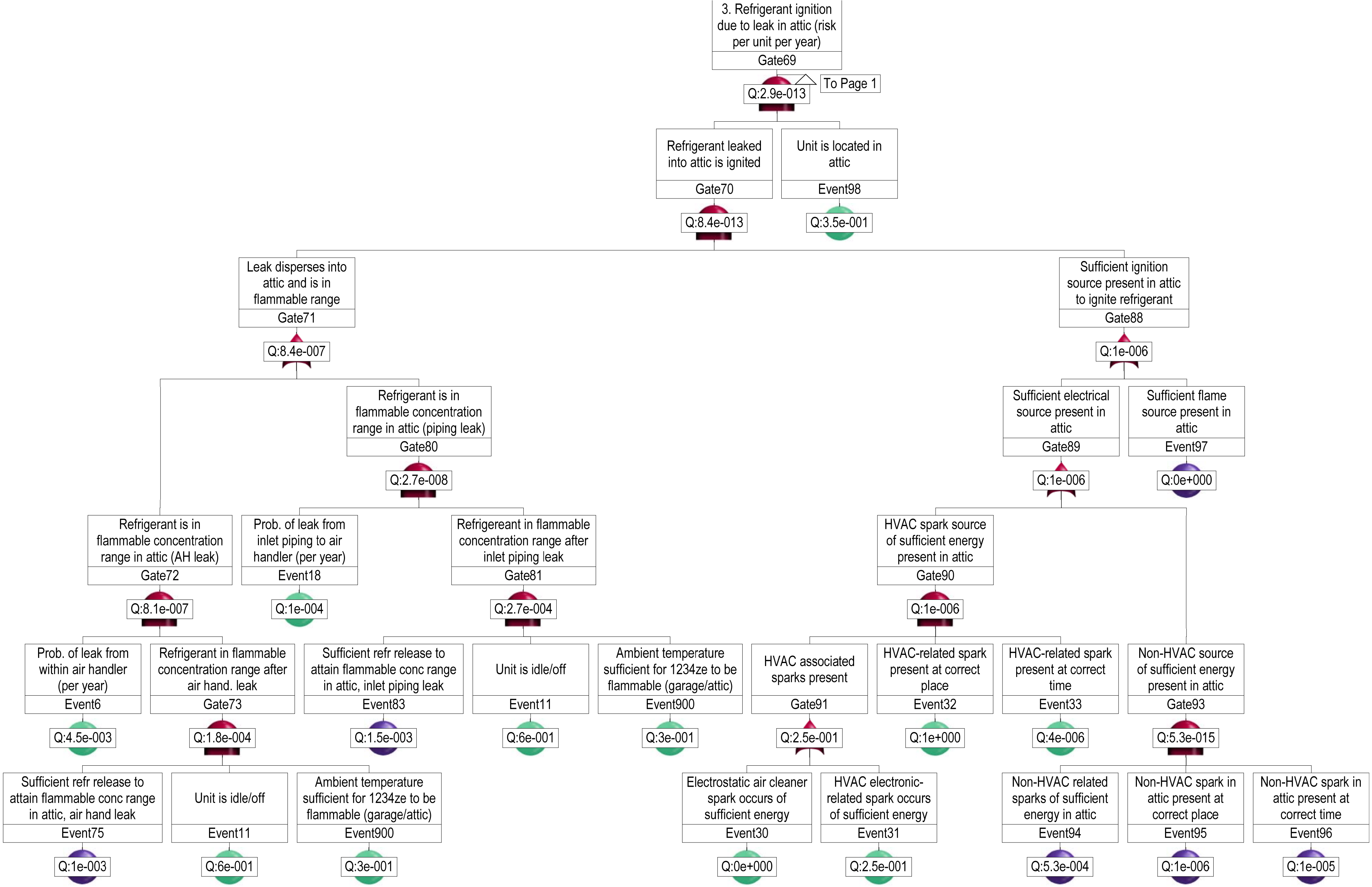

R. Refrigerant ignition during servicing (risk per unit per year)
Gate186
Q:4.9e-012
To Page 1
Probability unit is serviced per year
Event187
Q:1e-001
Refrigerant ignition during service
Gate188
Q:4.9e-011
Refrigerant ignition due to brazing of fitting indoors
Gate189
Q:6.8e-012
Refrigerant ignition by propane torch leak test
Gate228
Q:3e-012
Fraction of service calls involving brazing indoors
Event190
Q:7.5e-002
Refrigerant concentration in flammable zone indoors
Gate191
Q:9e-007
Service person uses brazing torch at relevant time indoors
Event194
Q:1e-004
Refrigerant ignition due to improper recovery or charging procedure (outdoors)
Gate204
Q:3.9e-011
From Page 12
Use of propane torch to test for leak
Gate229
Q:1e-009
Fraction of service calls involving a moderate or large leak
Event232
Q:1e-002
Service person recharges leak prior to looking for leak with flammable refrigerant
Event400
Q:3e-001
Sufficient refrigerant involved (indoors)
Event192
Q:1e-006
No dispersion by indoor air currents (e.g., fan)
Event193
Q:9e-001
Refrigerant ignition due to brazing of fitting outdoors
Gate197
Q:4.2e-013
Service person routinely uses torch to test for leaks
Event230
Q:1e-004
Serviceman believes refrigerant is non-flammable
Event231
Q:1e-004
Large leak is not detected by other means
Event401
Q:1e-001
Fraction of service calls involving brazing outdoors
Event198
Q:7e-002
Refrigerant concentration in flammable zone outdoors
Gate199
Q:6e-008
Service person uses brazing torch at relevant time outdoors
Event202
Q:1e-004
Sufficient refrigerant involved (outdoors)
Event200
Q:1e-006
No dispersion by wind
Event132
Q:6e-002

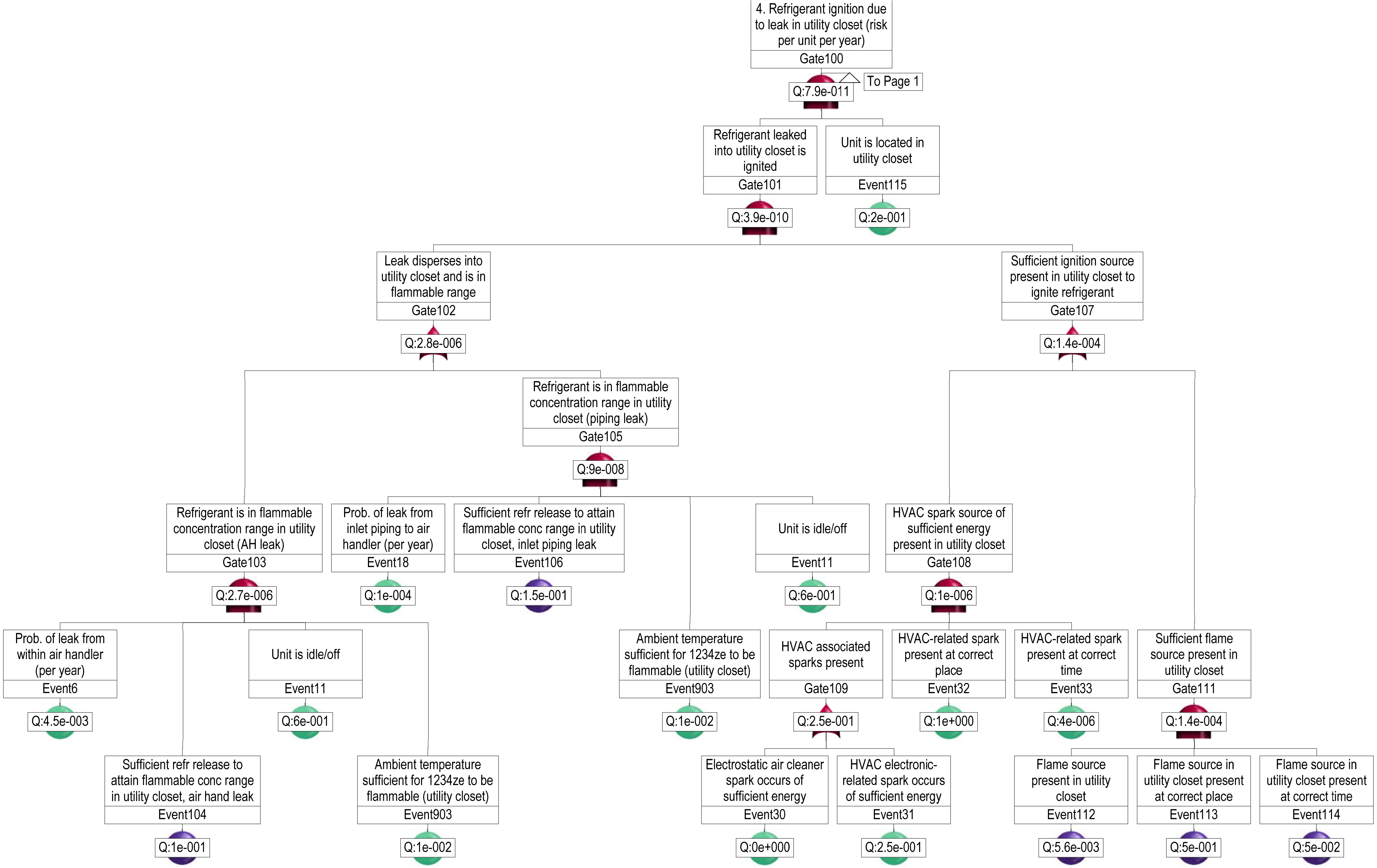

Refrigerant ignition due to improper recovery or charging procedure (outdoors)
Gate204
Q:3.9e-011
To Page 11
Leak outdoors from charging/recovery
Gate205
Q:9.3e-003
No dispersion by wind
Event201
Q:6e-002
Refrigerant concentration in flammable range (service scenario)
Event216
Q:1e+000
Match ignition source present and can ignite refrigerant
Gate218
Q:7e-008
Leak of refrigerant due to improper charging during a service call
Gate206
Q:7.6e-003
Leak of refrigerant due to improper recovery during a service call
Gate211
Q:1.6e-003
Service person smokes during repair and uses a match to light cigarette
Event219
Q:1e-002
Match struck at relevant time (service)
Event220
Q:7e-003
Match struck at relevant place (service)
Event221
Q:1e-003
Fraction of service calls involving charging
Event207
Q:1.5e-001
Release refrigerant to atmosphere due to improper charging
Gate208
Q:5.1e-002
Fraction of service calls that involve recovery
Event212
Q:1.5e-001
Release refrigerant to atmosphere during recovery
Gate213
Q:1.1e-002
Service person removes hose without closing cylinder valve
Event209
Q:1e-003
Initial charge vented to atmosphere
Event210
Q:5e-002
Leak while recovering to a closed container
Event214
Q:1e-003
Deliberately vent to atmosphere
Event215
Q:1e-002

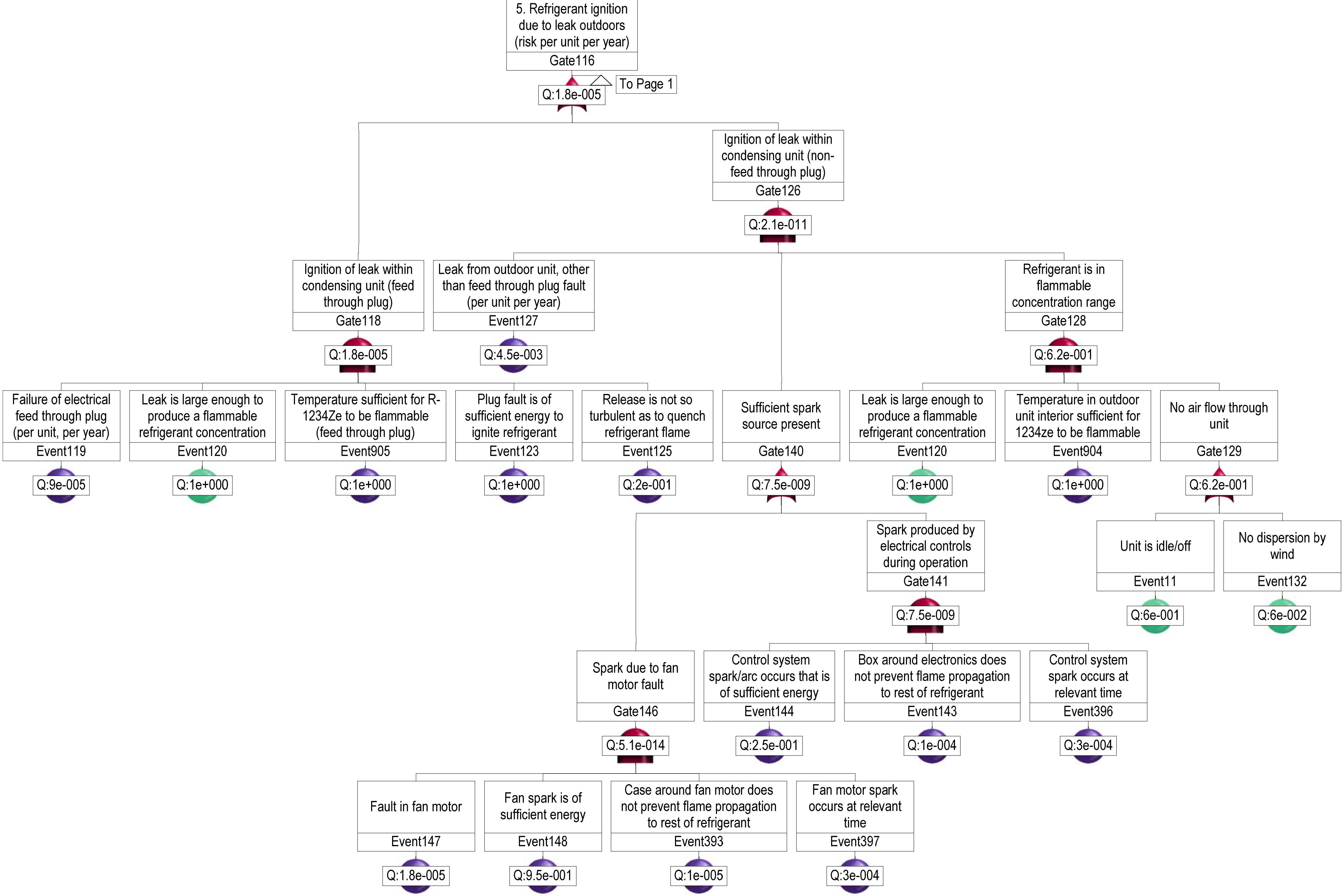

Overall risk of refrigerant ignition (risk per unit per year)
Gate1
Q:1.8e-005
1. Refrigerant ignition due to leak in garage (risk per unit per year)
Gate2
Q:3.1e-013
From Page 2
2. Refrigerant ignition due to leak in basement (risk per unit per year)
Gate47
Q:7.3e-014
From Page 3
3. Refrigerant ignition due to leak in attic (risk per unit per year)
Gate69
Q:2.9e-013
From Page 4
4. Refrigerant ignition due to leak in utility closet (risk per unit per year)
Gate100
Q:7.9e-011
From Page 5
5. Refrigerant ignition due to leak outdoors (risk per unit per year)
Gate116
Q:1.8e-005
From Page 6
6. Refrigerant ignition in room providing return air (risk per unit per year)
Gate150
Q:2.7e-018
From Page 7
7. Refrigerant ignition due to leak from piping in wall (risk per unit per year)
Gate163
Q:1.2e-016
From Page 8
8. Refrigerant ignition in room due to leak into duct while unit is operating (risk per unit per year)
Gate172
Q:4.2e-020
From Page 9
9. Refrigerant ignition within air handler (risk per unit per year)
Gate176
Q:2.3e-010
From Page 10
R. Refrigerant ignition during servicing (risk per unit per year)
Gate186
Q:6e-013
From Page 11

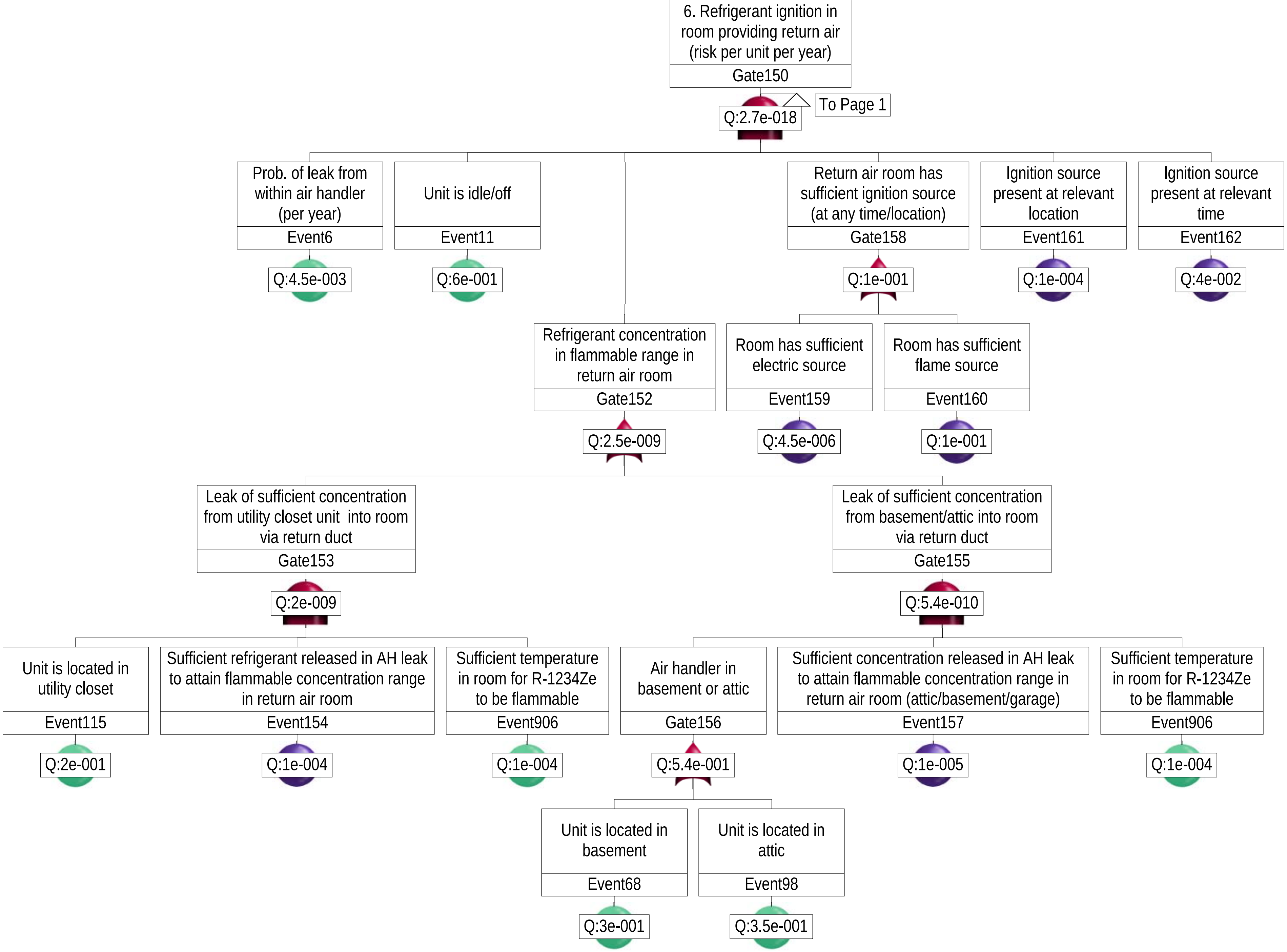

1. Refrigerant ignition due to leak in garage (risk per unit per year)
Gate2
Q:3.1e-013
To Page 1
Refrigerant leaked into garage is ignited
Gate3
Q:2.1e-012
Unit is located in garage
Event45
Q:1.5e-001
Leak disperses into garage and is in flammable range
Gate4
Q:1.7e-006
Refrigerant is in flammable concentration range in garage (air handler leak)
Gate5
Q:1.6e-006
Refrigerant is in flammable concentration range in garage (piping leak)
Gate17
Q:5.4e-008
Sufficient ignition source present in garage to ignite refrigerant
Gate26
Q:1.2e-006
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Refrigerant in flammable concentration range after air hand. leak
Gate7
Q:1.2e-003
Ambient temperature sufficient for 1234ze to be flammable (garage/attic)
Event900
Q:3e-001
Prob. of leak from inlet piping to air handler (per year)
Event18
Q:1e-004
Refrigerant in flammable concentration range after inlet piping leak
Gate19
Q:1.8e-003
Ambient temperature sufficient for 1234ze to be flammable (garage/attic)
Event900
Q:3e-001
Sufficient electrical source present in garage
Gate27
Q:1e-006
Sufficient refr release to attain flammable conc range in garage, air hand leak
Event9
Q:2e-003
Unit is idle/off
Event11
Q:6e-001
Sufficient refr release to attain flammable conc range in garage, inlet piping leak
Event21
Q:3e-003
Unit is idle/off
Event11
Q:6e-001
HVAC spark source of sufficient energy present in garage
Gate28
Q:1e-006
Sufficient flame source present in garage
Gate41
Q:2.3e-007
HVAC associated sparks present
Gate29
Q:2.5e-001
HVAC-related spark present at correct place
Event32
Q:1e+000
HVAC-related spark present at correct time
Event33
Q:4e-006
Non-HVAC source of sufficient energy present in garage
Gate35
Q:2.3e-011
Flame source present in garage
Event42
Q:4.5e-003
Flame source in garage present at correct place
Event43
Q:1e-003
Flame source in garage present at correct time
Event44
Q:5e-002
Electrostatic air cleaner spark occurs of sufficient energy
Event30
Q:0e+000
HVAC electronic-related spark occurs of sufficient energy
Event31
Q:2.5e-001
Non-HVAC related spark occurs in garage of sufficient energy
Event36
Q:1e-004
Non-HVAC spark in garage present at correct place
Event37
Q:1e-003
Non-HVAC spark in garage present at correct time
Event38
Q:2.3e-004

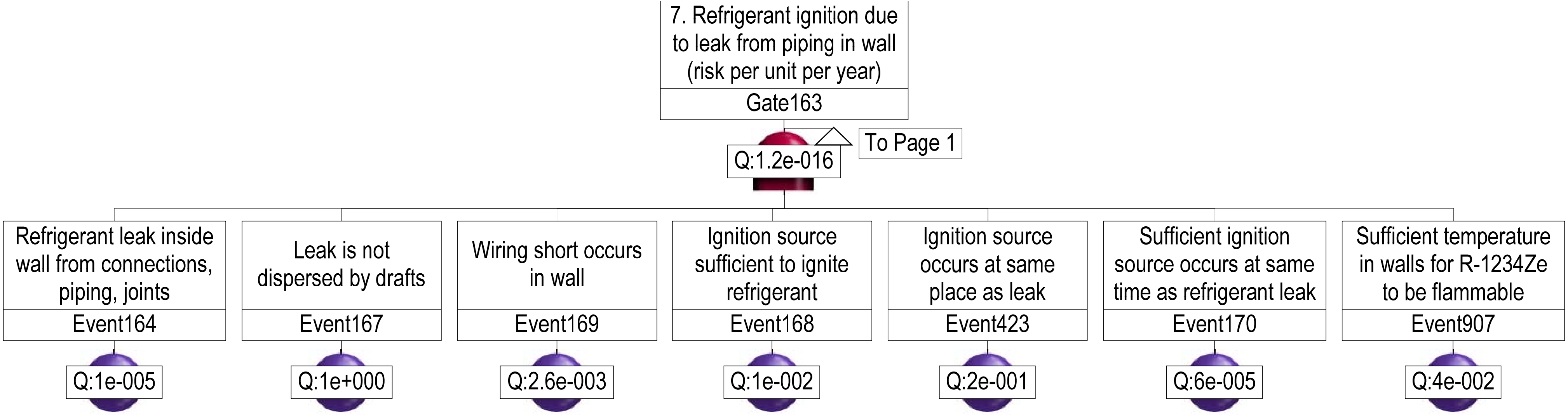

2. Refrigerant ignition due to leak in basement (risk per unit per year)
Gate47
Q:7.3e-014
To Page 1
Refrigerant leaked into basement is ignited
Gate48
Q:2.4e-013
Unit is located in basement
Event68
Q:3e-001
Leak disperses into basement and is in flammable range
Gate49
Q:1.7e-007
Sufficient ignition source present in basement to ignite refrigerant
Gate54
Q:1.5e-006
Refrigerant is in flammable concentration range in basement (AH leak)
Gate50
Q:1.6e-007
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Sufficient refr release to attain flammable conc range in basement, air hand leak
Event51
Q:2e-003
Unit is idle/off
Event11
Q:6e-001
Ambient temperature sufficient for 1234ze to be flammable (basement)
Event901
Q:3e-002
Refrigerant is in flammable concentration range in basement (piping leak)
Gate52
Q:5.4e-009
Prob. of leak from inlet piping to air handler (per year)
Event18
Q:1e-004
Sufficient refr release to attain flammable conc range in basement, inlet piping leak
Event53
Q:3e-003
Unit is idle/off
Event11
Q:6e-001
Ambient temperature sufficient for 1234ze to be flammable (basement)
Event901
Q:3e-002
Sufficient electrical source present in basement
Gate55
Q:1e-006
HVAC spark source of sufficient energy present in basement
Gate56
Q:1e-006
HVAC associated sparks present
Gate57
Q:2.5e-001
Electrostatic air cleaner spark occurs of sufficient energy
Event30
Q:0e+000
HVAC electronic-related spark occurs of sufficient energy
Event31
Q:2.5e-001
HVAC-related spark present at correct place
Event32
Q:1e+000
HVAC-related spark present at correct time
Event33
Q:4e-006
Non-HVAC source of sufficient energy present in basement
Gate59
Q:2.3e-011
Non-HVAC related sparks of sufficient energy in basement (e.g., owner activities)
Event60
Q:1e-004
Non-HVAC spark in basement present at correct place
Event62
Q:1e-003
Non-HVAC spark in basement present at correct time
Event61
Q:2.3e-004
Sufficient flame source present in basement
Gate64
Q:4.5e-007
Flame source present in basement sufficient to ignite refrigerant
Event65
Q:4.5e-003
Flame source in basement present at correct place
Event66
Q:1e-003
Flame source in basement present at correct time
Event67
Q:1e-001

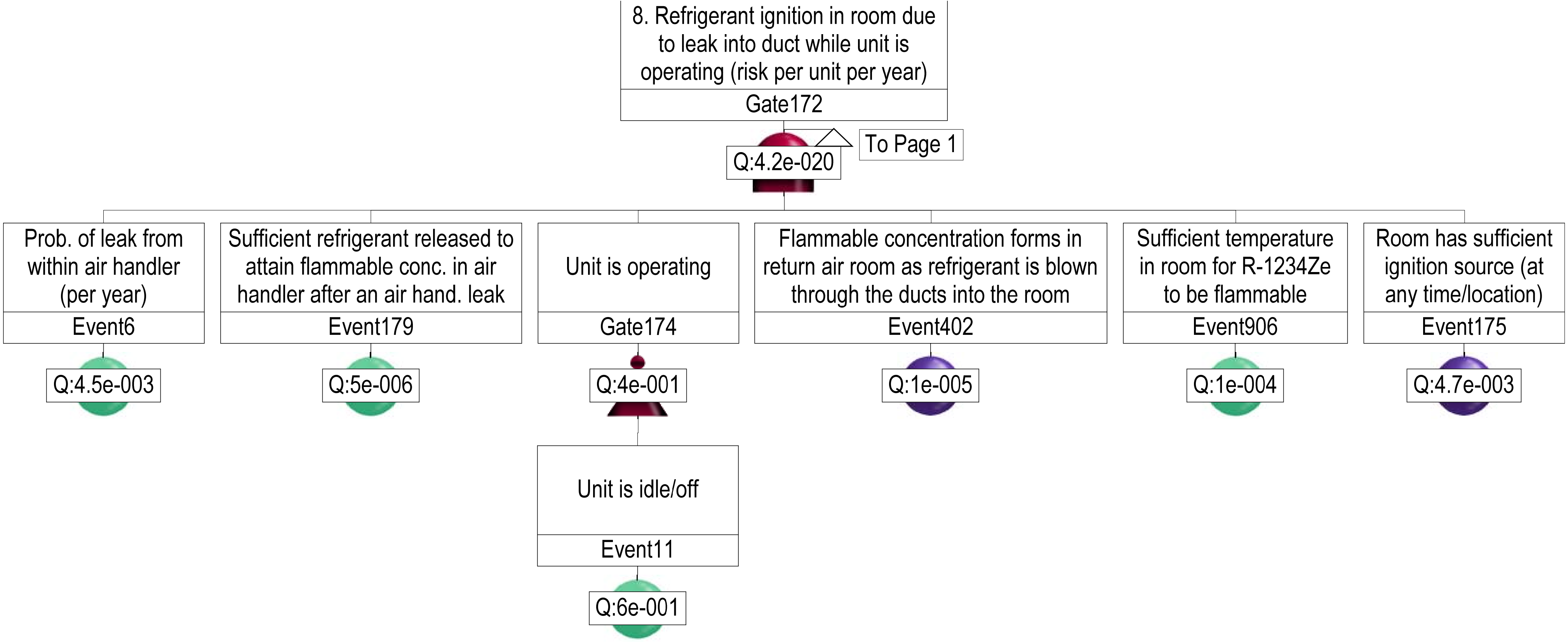

3. Refrigerant ignition due to leak in attic (risk per unit per year)
Gate69
Q:2.9e-013
To Page 1
Refrigerant leaked into attic is ignited
Gate70
Q:8.4e-013
Unit is located in attic
Event98
Q:3.5e-001
Leak disperses into attic and is in flammable range
Gate71
Q:8.4e-007
Sufficient ignition source present in attic to ignite refrigerant
Gate88
Q:1e-006
Refrigerant is in flammable concentration range in attic (piping leak)
Gate80
Q:2.7e-008
Sufficient electrical source present in attic
Gate89
Q:1e-006
Sufficient flame source present in attic
Event97
Q:0e+000
Refrigerant is in flammable concentration range in attic (AH leak)
Gate72
Q:8.1e-007
Prob. of leak from inlet piping to air handler (per year)
Event18
Q:1e-004
Refrigereant in flammable concentration range after inlet piping leak
Gate81
Q:2.7e-004
HVAC spark source of sufficient energy present in attic
Gate90
Q:1e-006
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Refrigerant in flammable concentration range after air hand. leak
Gate73
Q:1.8e-004
Sufficient refr release to attain flammable conc range in attic, inlet piping leak
Event83
Q:1.5e-003
Unit is idle/off
Event11
Q:6e-001
Ambient temperature sufficient for 1234ze to be flammable (garage/attic)
Event900
Q:3e-001
HVAC associated sparks present
Gate91
Q:2.5e-001
HVAC-related spark present at correct place
Event32
Q:1e+000
HVAC-related spark present at correct time
Event33
Q:4e-006
Non-HVAC source of sufficient energy present in attic
Gate93
Q:5.3e-015
Sufficient refr release to attain flammable conc range in attic, air hand leak
Event75
Q:1e-003
Unit is idle/off
Event11
Q:6e-001
Ambient temperature sufficient for 1234ze to be flammable (garage/attic)
Event900
Q:3e-001
Electrostatic air cleaner spark occurs of sufficient energy
Event30
Q:0e+000
HVAC electronic-related spark occurs of sufficient energy
Event31
Q:2.5e-001
Non-HVAC related sparks of sufficient energy in attic
Event94
Q:5.3e-004
Non-HVAC spark in attic present at correct place
Event95
Q:1e-006
Non-HVAC spark in attic present at correct time
Event96
Q:1e-005

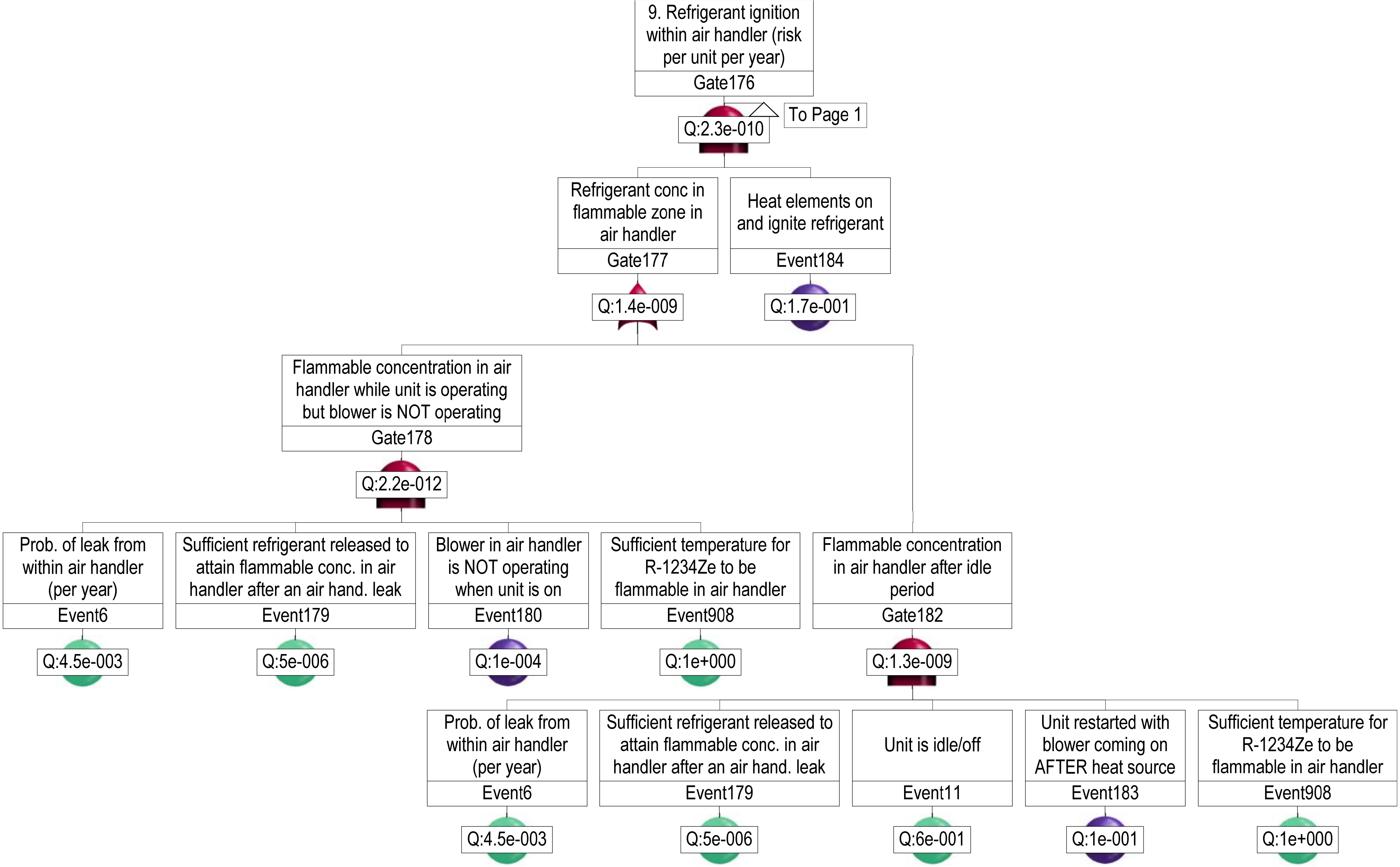

4. Refrigerant ignition due to leak in utility closet (risk per unit per year)
Gate100
Q:7.9e-011
To Page 1
Refrigerant leaked into utility closet is ignited
Gate101
Q:3.9e-010
Unit is located in utility closet
Event115
Q:2e-001
Leak disperses into utility closet and is in flammable range
Gate102
Q:2.8e-006
Sufficient ignition source present in utility closet to ignite refrigerant
Gate107
Q:1.4e-004
Refrigerant is in flammable concentration range in utility closet (piping leak)
Gate105
Q:9e-008
Refrigerant is in flammable concentration range in utility closet (AH leak)
Gate103
Q:2.7e-006
Prob. of leak from inlet piping to air handler (per year)
Event18
Q:1e-004
Sufficient refr release to attain flammable conc range in utility closet, inlet piping leak
Event106
Q:1.5e-001
Unit is idle/off
Event11
Q:6e-001
HVAC spark source of sufficient energy present in utility closet
Gate108
Q:1e-006
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Unit is idle/off
Event11
Q:6e-001
Ambient temperature sufficient for 1234ze to be flammable (utility closet)
Event903
Q:1e-002
HVAC associated sparks present
Gate109
Q:2.5e-001
HVAC-related spark present at correct place
Event32
Q:1e+000
HVAC-related spark present at correct time
Event33
Q:4e-006
Sufficient flame source present in utility closet
Gate111
Q:1.4e-004
Sufficient refr release to attain flammable conc range in utility closet, air hand leak
Event104
Q:1e-001
Ambient temperature sufficient for 1234ze to be flammable (utility closet)
Event903
Q:1e-002
Electrostatic air cleaner spark occurs of sufficient energy
Event30
Q:0e+000
HVAC electronic-related spark occurs of sufficient energy
Event31
Q:2.5e-001
Flame source present in utility closet
Event112
Q:5.6e-003
Flame source in utility closet present at correct place
Event113
Q:5e-001
Flame source in utility closet present at correct time
Event114
Q:5e-002

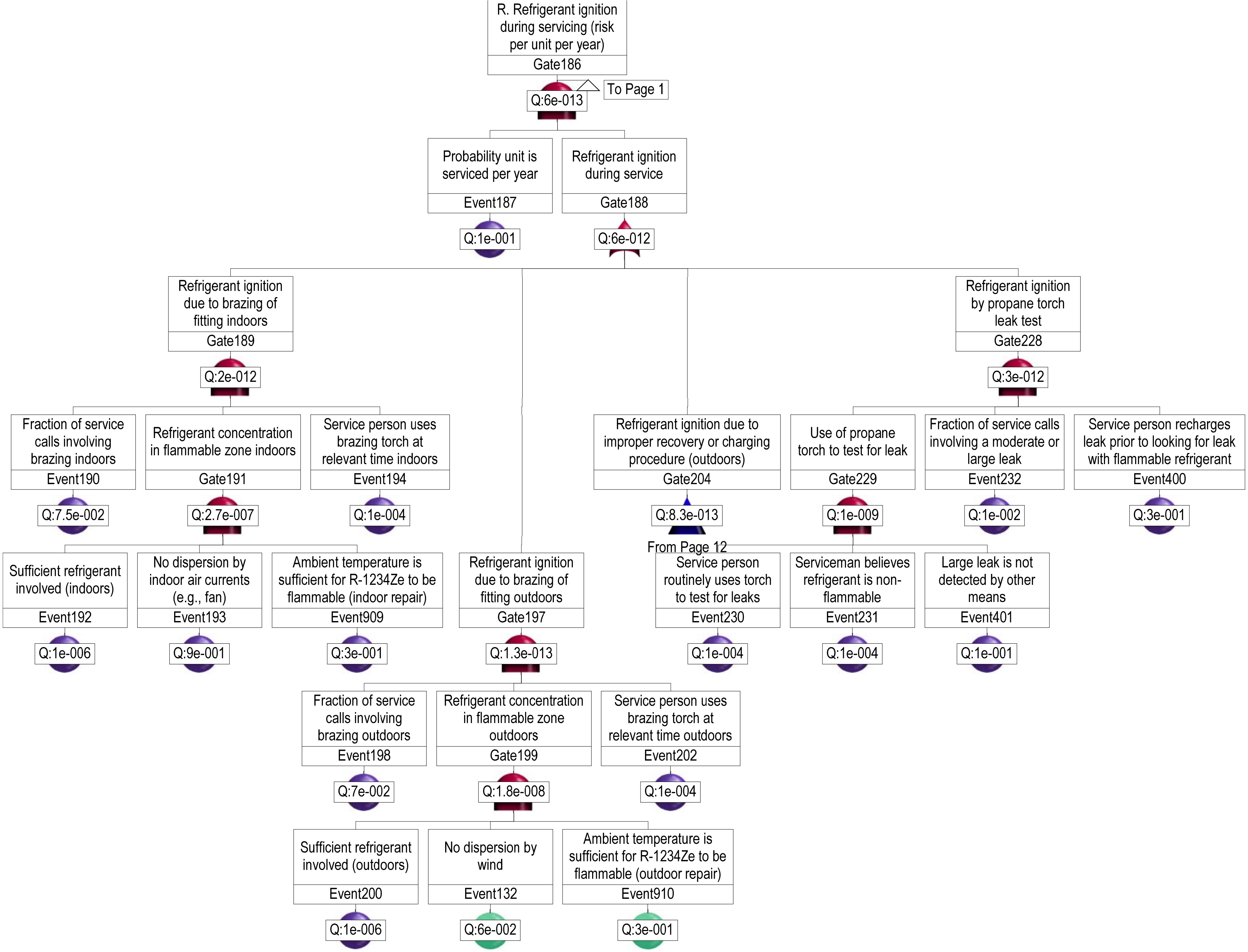

5. Refrigerant ignition due to leak outdoors (risk per unit per year)
Gate116
Q:1.8e-005
To Page 1
Ignition of leak within condensing unit (non-feed through plug)
Gate126
Q:2.1e-011
Ignition of leak within condensing unit (feed through plug)
Gate118
Q:1.8e-005
Leak from outdoor unit, other than feed through plug fault (per unit per year)
Event127
Q:4.5e-003
Refrigerant is in flammable concentration range
Gate128
Q:6.2e-001
Failure of electrical feed through plug (per unit, per year)
Event119
Q:9e-005
Leak is large enough to produce a flammable refrigerant concentration
Event120
Q:1e+000
Temperature sufficient for R-1234Ze to be flammable (feed through plug)
Event905
Q:1e+000
Plug fault is of sufficient energy to ignite refrigerant
Event123
Q:1e+000
Release is not so turbulent as to quench refrigerant flame
Event125
Q:2e-001
Sufficient spark source present
Gate140
Q:7.5e-009
Leak is large enough to produce a flammable refrigerant concentration
Event120
Q:1e+000
Temperature in outdoor unit interior sufficient for 1234ze to be flammable
Event904
Q:1e+000
No air flow through unit
Gate129
Q:6.2e-001
Spark produced by electrical controls during operation
Gate141
Q:7.5e-009
Unit is idle/off
Event11
Q:6e-001
No dispersion by wind
Event132
Q:6e-002
Spark due to fan motor fault
Gate146
Q:5.1e-014
Control system spark/arc occurs that is of sufficient energy
Event144
Q:2.5e-001
Box around electronics does not prevent flame propagation to rest of refrigerant
Event143
Q:1e-004
Control system spark occurs at relevant time
Event396
Q:3e-004
Fault in fan motor
Event147
Q:1.8e-005
Fan spark is of sufficient energy
Event148
Q:9.5e-001
Case around fan motor does not prevent flame propagation to rest of refrigerant
Event393
Q:1e-005
Fan motor spark occurs at relevant time
Event397
Q:3e-004

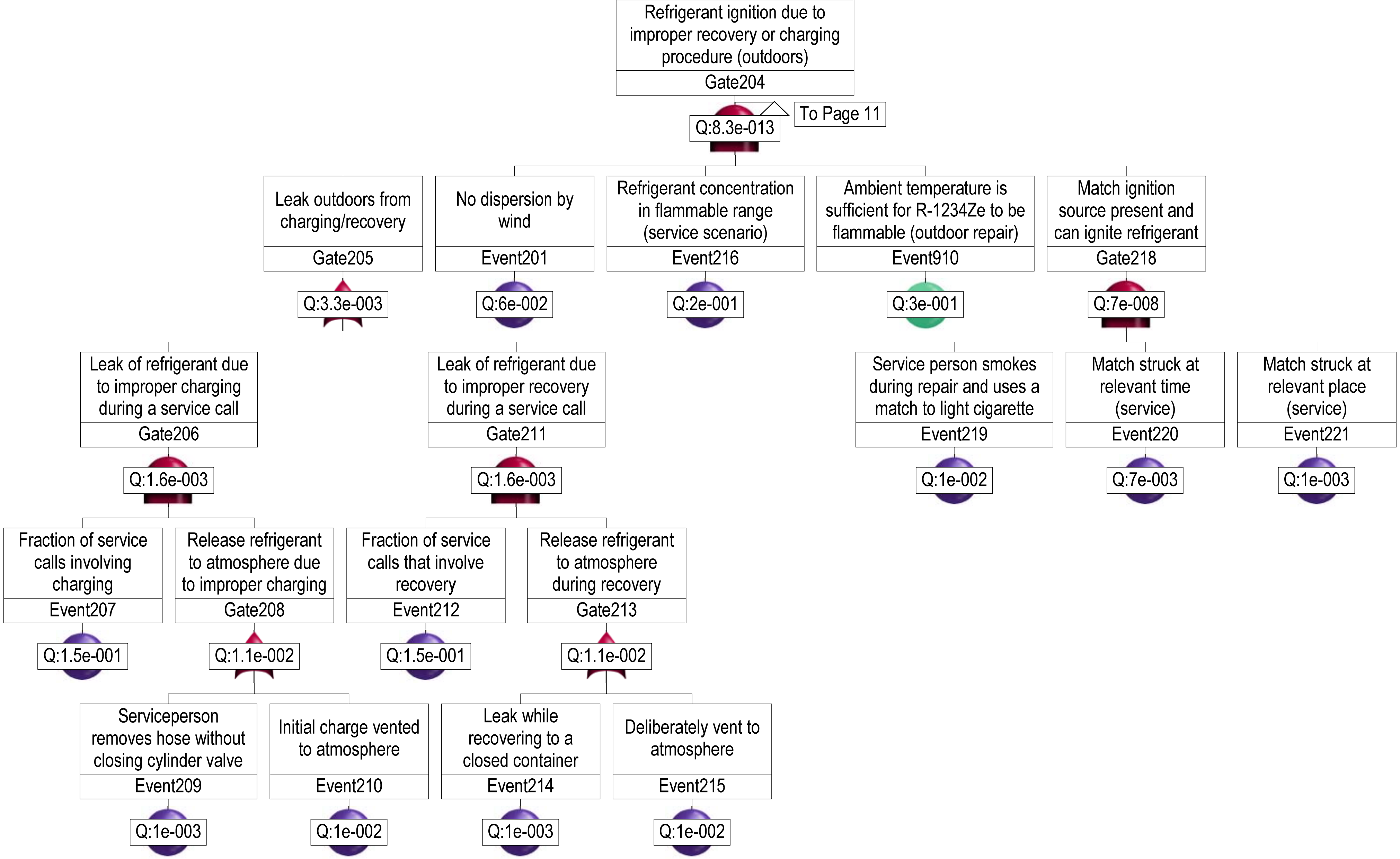

6. Refrigerant ignition in room providing return air (risk per unit per year)
Gate150
Q:2.7e-018
To Page 1
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Unit is idle/off
Event11
Q:6e-001
Return air room has sufficient ignition source (at any time/location)
Gate158
Q:1e-001
Ignition source present at relevant location
Event161
Q:1e-004
Ignition source present at relevant time
Event162
Q:4e-002
Refrigerant concentration in flammable range in return air room
Gate152
Q:2.5e-009
Room has sufficient electric source
Event159
Q:4.5e-006
Room has sufficient flame source
Event160
Q:1e-001
Leak of sufficient concentration from utility closet unit into room via return duct
Gate153
Q:2e-009
Leak of sufficient concentration from basement/attic into room via return duct
Gate155
Q:5.4e-010
Unit is located in utility closet
Event115
Q:2e-001
Sufficient refrigerant released in AH leak to attain flammable concentration range in return air room
Event154
Q:1e-004
Sufficient temperature in room for R-1234Ze to be flammable
Event906
Q:1e-004
Air handler in basement or attic
Gate156
Q:5.4e-001
Sufficient concentration released in AH leak to attain flammable concentration range in return air room (attic/basement/garage)
Event157
Q:1e-005
Sufficient temperature in room for R-1234Ze to be flammable
Event906
Q:1e-004
Unit is located in basement
Event68
Q:3e-001
Unit is located in attic
Event98
Q:3.5e-001

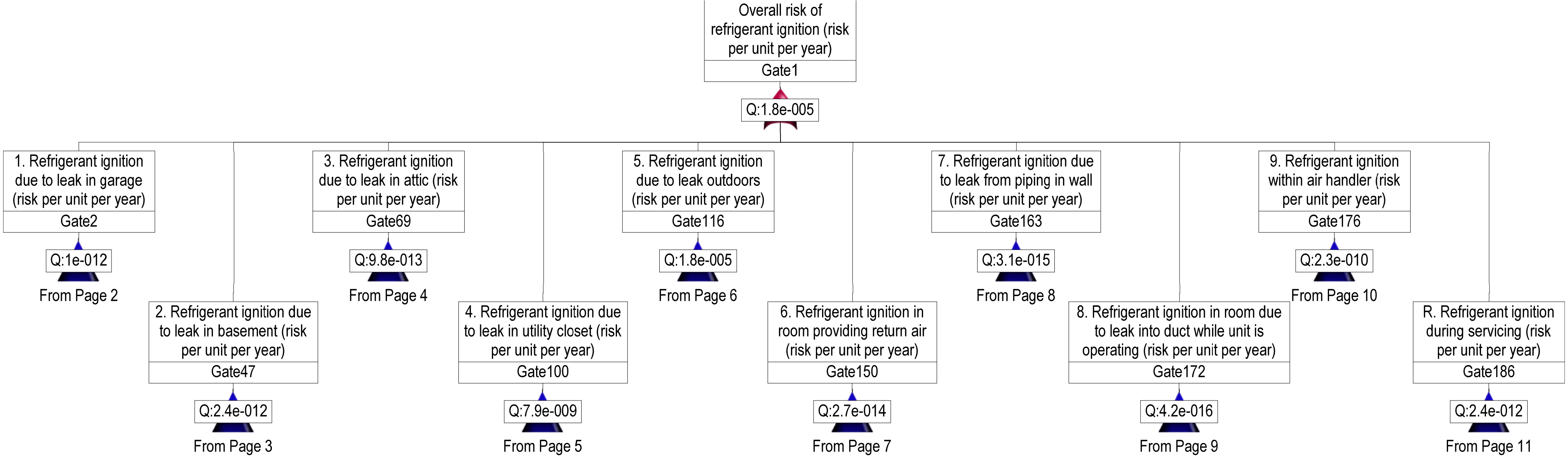

7. Refrigerant ignition due to leak from piping in wall (risk per unit per year)
Gate163
Q:1.2e-016
To Page 1
Refrigerant leak inside wall from connections, piping, joints
Event164
Q:1e-005
Leak is not dispersed by drafts
Event167
Q:1e+000
Wiring short occurs in wall
Event169
Q:2.6e-003
Ignition source sufficient to ignite refrigerant
Event168
Q:1e-002
Ignition source occurs at same place as leak
Event423
Q:2e-001
Sufficient ignition source occurs at same time as refrigerant leak
Event170
Q:6e-005
Sufficient temperature in walls for R-1234Ze to be flammable
Event907
Q:4e-002

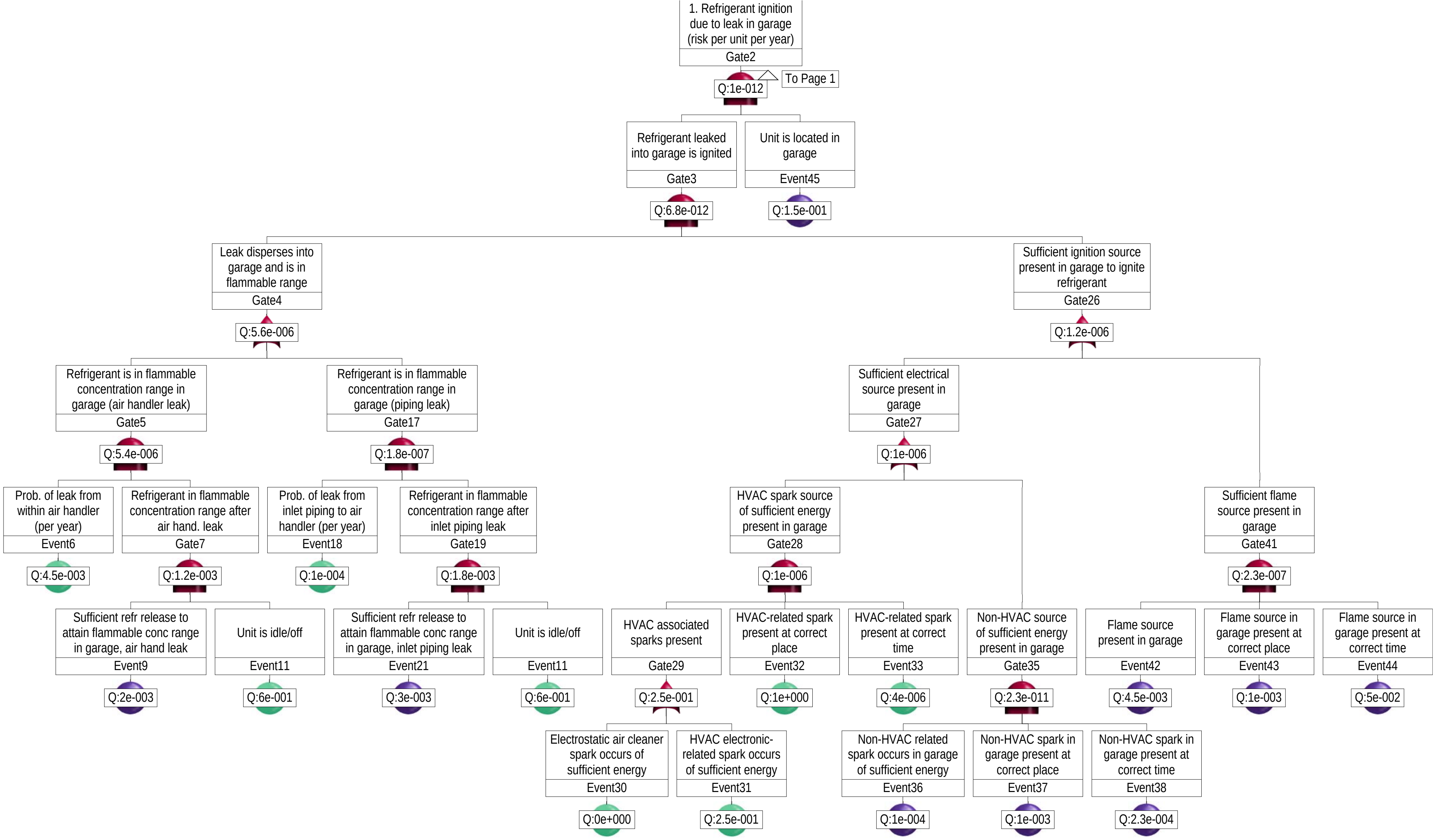

8. Refrigerant ignition in room due to leak into duct while unit is operating (risk per unit per year)
Gate172
Q:4.2e-020
To Page 1
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Sufficient refrigerant released to attain flammable conc. in air handler after an air hand. leak
Event179
Q:5e-006
Unit is operating
Gate174
Q:4e-001
Flammable concentration forms in return air room as refrigerant is blown through the ducts into the room
Event402
Q:1e-005
Sufficient temperature in room for R-1234Ze to be flammable
Event906
Q:1e-004
Room has sufficient ignition source (at any time/location)
Event175
Q:4.7e-003
Unit is idle/off
Event11
Q:6e-001

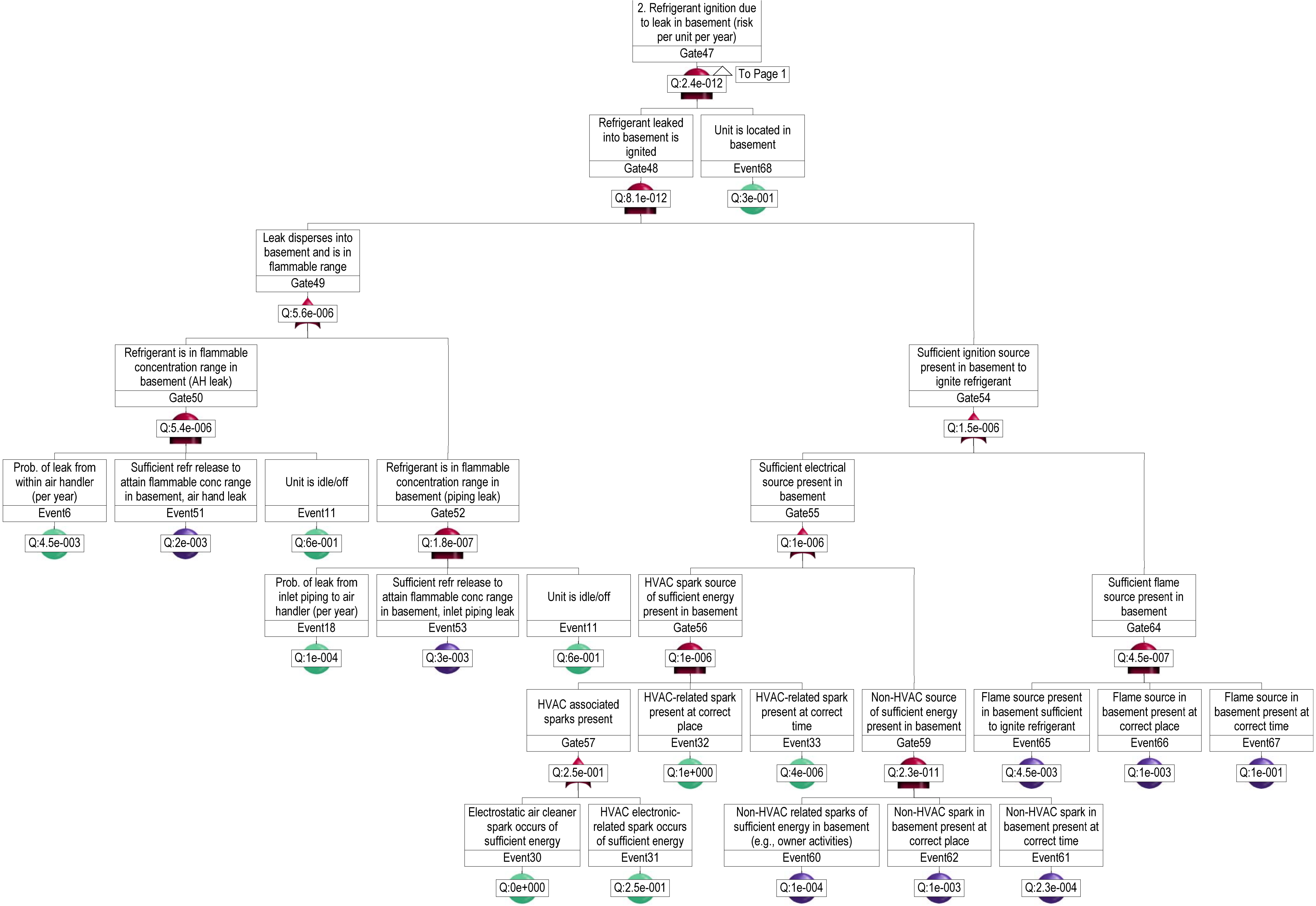

9. Refrigerant ignition within air handler (risk per unit per year)
Gate176
Q:2.3e-010
To Page 1
Refrigerant conc in flammable zone in air handler
Gate177
Q:1.4e-009
Heat elements on and ignite refrigerant
Event184
Q:1.7e-001
Flammable concentration in air handler while unit is operating but blower is NOT operating
Gate178
Q:2.2e-012
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Sufficient refrigerant released to attain flammable conc. in air handler after an air hand. leak
Event179
Q:5e-006
Blower in air handler is NOT operating when unit is on
Event180
Q:1e-004
Sufficient temperature for R-1234Ze to be flammable in air handler
Event908
Q:1e+000
Flammable concentration in air handler after idle period
Gate182
Q:1.3e-009
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Sufficient refrigerant released to attain flammable conc. in air handler after an air hand. leak
Event179
Q:5e-006
Unit is idle/off
Event11
Q:6e-001
Unit restarted with blower coming on AFTER heat source
Event183
Q:1e-001
Sufficient temperature for R-1234Ze to be flammable in air handler
Event908
Q:1e+000

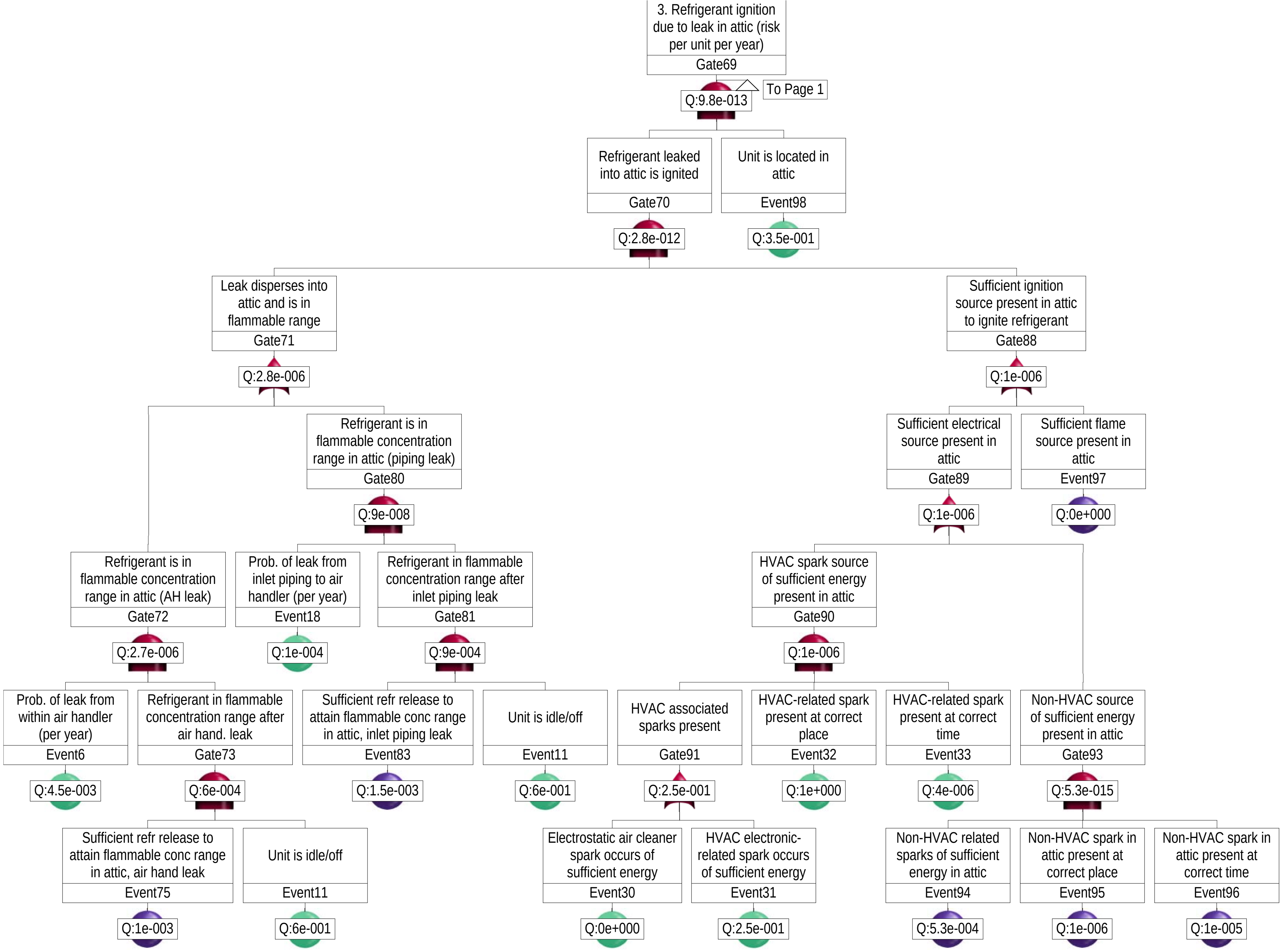

R. Refrigerant ignition during servicing (risk per unit per year)
Gate186
Q:6e-013
To Page 1
Probability unit is serviced per year
Event187
Q:1e-001
Refrigerant ignition during service
Gate188
Q:6e-012
Refrigerant ignition due to brazing of fitting indoors
Gate189
Q:2e-012
Refrigerant ignition by propane torch leak test
Gate228
Q:3e-012
Fraction of service calls involving brazing indoors
Event190
Q:7.5e-002
Refrigerant concentration in flammable zone indoors
Gate191
Q:2.7e-007
Service person uses brazing torch at relevant time indoors
Event194
Q:1e-004
Refrigerant ignition due to improper recovery or charging procedure (outdoors)
Gate204
Q:8.3e-013
From Page 12
Use of propane torch to test for leak
Gate229
Q:1e-009
Fraction of service calls involving a moderate or large leak
Event232
Q:1e-002
Service person recharges leak prior to looking for leak with flammable refrigerant
Event400
Q:3e-001
Sufficient refrigerant involved (indoors)
Event192
Q:1e-006
No dispersion by indoor air currents (e.g., fan)
Event193
Q:9e-001
Ambient temperature is sufficient for R-1234Ze to be flammable (indoor repair)
Event909
Q:3e-001
Refrigerant ignition due to brazing of fitting outdoors
Gate197
Q:1.3e-013
Service person routinely uses torch to test for leaks
Event230
Q:1e-004
Serviceman believes refrigerant is non-flammable
Event231
Q:1e-004
Large leak is not detected by other means
Event401
Q:1e-001
Fraction of service calls involving brazing outdoors
Event198
Q:7e-002
Refrigerant concentration in flammable zone outdoors
Gate199
Q:1.8e-008
Service person uses brazing torch at relevant time outdoors
Event202
Q:1e-004
Sufficient refrigerant involved (outdoors)
Event200
Q:1e-006
No dispersion by wind
Event132
Q:6e-002
Ambient temperature is sufficient for R-1234Ze to be flammable (outdoor repair)
Event910
Q:3e-001

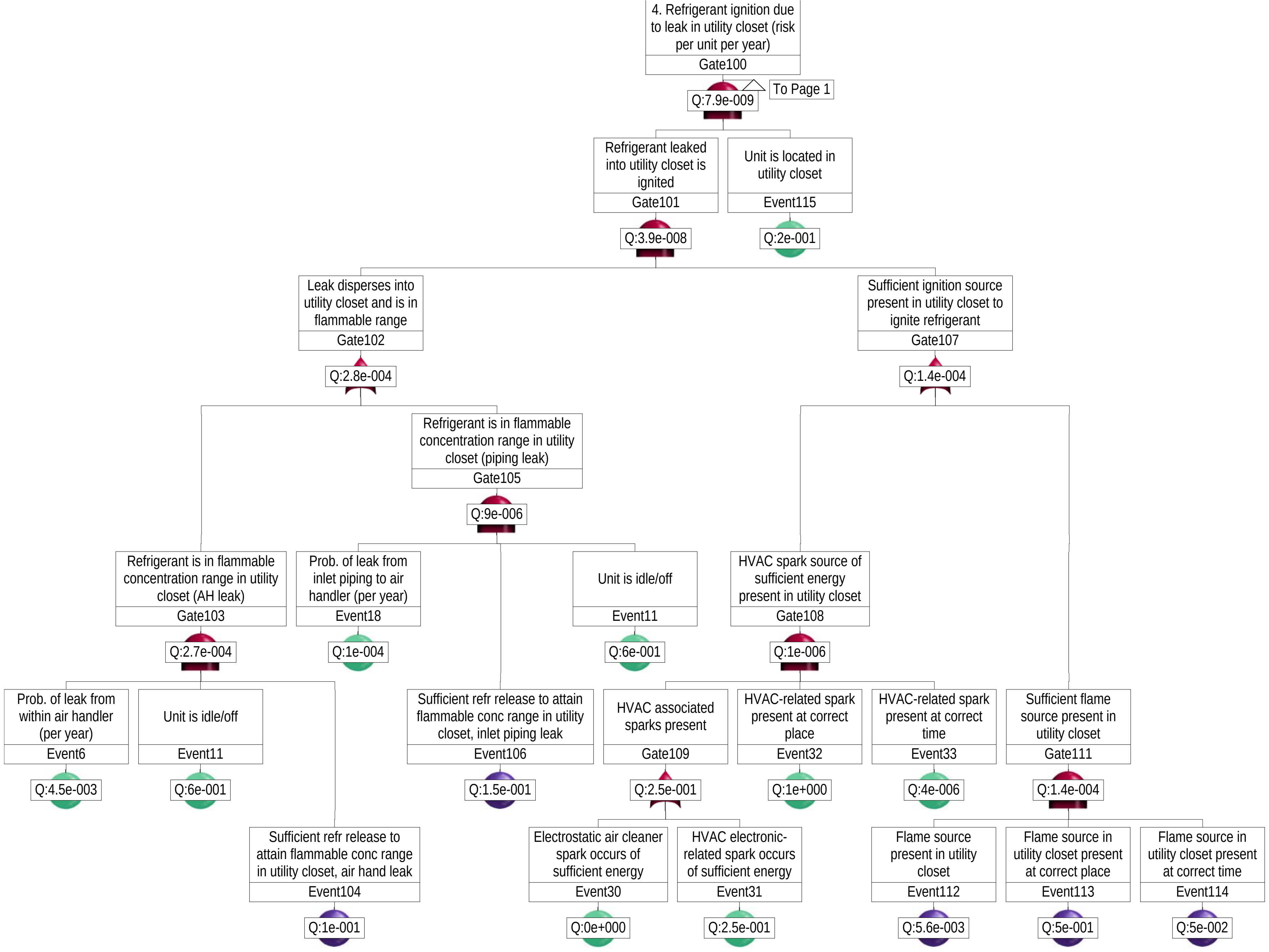

Refrigerant ignition due to improper recovery or charging procedure (outdoors)
Gate204
Q:8.3e-013
To Page 11
Leak outdoors from charging/recovery
Gate205
Q:3.3e-003
No dispersion by wind
Event201
Q:6e-002
Refrigerant concentration in flammable range (service scenario)
Event216
Q:2e-001
Ambient temperature is sufficient for R-1234Ze to be flammable (outdoor repair)
Event910
Q:3e-001
Match ignition source present and can ignite refrigerant
Gate218
Q:7e-008
Leak of refrigerant due to improper charging during a service call
Gate206
Q:1.6e-003
Leak of refrigerant due to improper recovery during a service call
Gate211
Q:1.6e-003
Service person smokes during repair and uses a match to light cigarette
Event219
Q:1e-002
Match struck at relevant time (service)
Event220
Q:7e-003
Match struck at relevant place (service)
Event221
Q:1e-003
Fraction of service calls involving charging
Event207
Q:1.5e-001
Release refrigerant to atmosphere due to improper charging
Gate208
Q:1.1e-002
Fraction of service calls that involve recovery
Event212
Q:1.5e-001
Release refrigerant to atmosphere during recovery
Gate213
Q:1.1e-002
Serviceperson removes hose without closing cylinder valve
Event209
Q:1e-003
Initial charge vented to atmosphere
Event210
Q:1e-002
Leak while recovering to a closed container
Event214
Q:1e-003
Deliberately vent to atmosphere
Event215
Q:1e-002

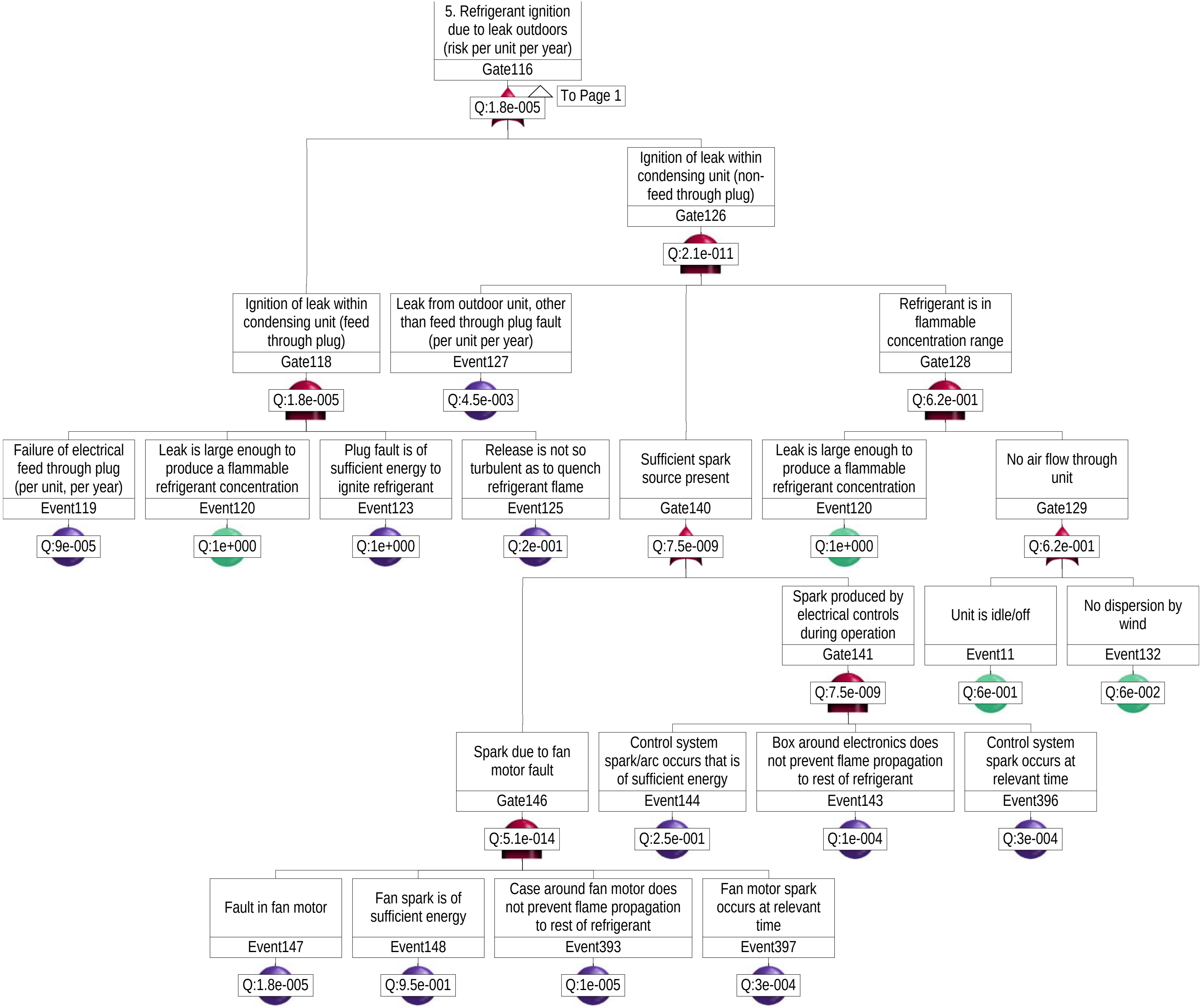

Overall risk of refrigerant ignition (risk per unit per year)
Gate1
Q:1.8e-005
1. Refrigerant ignition due to leak in garage (risk per unit per year)
Gate2
Q:1e-012
From Page 2
2. Refrigerant ignition due to leak in basement (risk per unit per year)
Gate47
Q:2.4e-012
From Page 3
3. Refrigerant ignition due to leak in attic (risk per unit per year)
Gate69
Q:9.8e-013
From Page 4
4. Refrigerant ignition due to leak in utility closet (risk per unit per year)
Gate100
Q:7.9e-009
From Page 5
5. Refrigerant ignition due to leak outdoors (risk per unit per year)
Gate116
Q:1.8e-005
From Page 6
6. Refrigerant ignition in room providing return air (risk per unit per year)
Gate150
Q:2.7e-014
From Page 7
7. Refrigerant ignition due to leak from piping in wall (risk per unit per year)
Gate163
Q:3.1e-015
From Page 8
8. Refrigerant ignition in room due to leak into duct while unit is operating (risk per unit per year)
Gate172
Q:4.2e-016
From Page 9
9. Refrigerant ignition within air handler (risk per unit per year)
Gate176
Q:2.3e-010
From Page 10
R. Refrigerant ignition during servicing (risk per unit per year)
Gate186
Q:2.4e-012
From Page 11

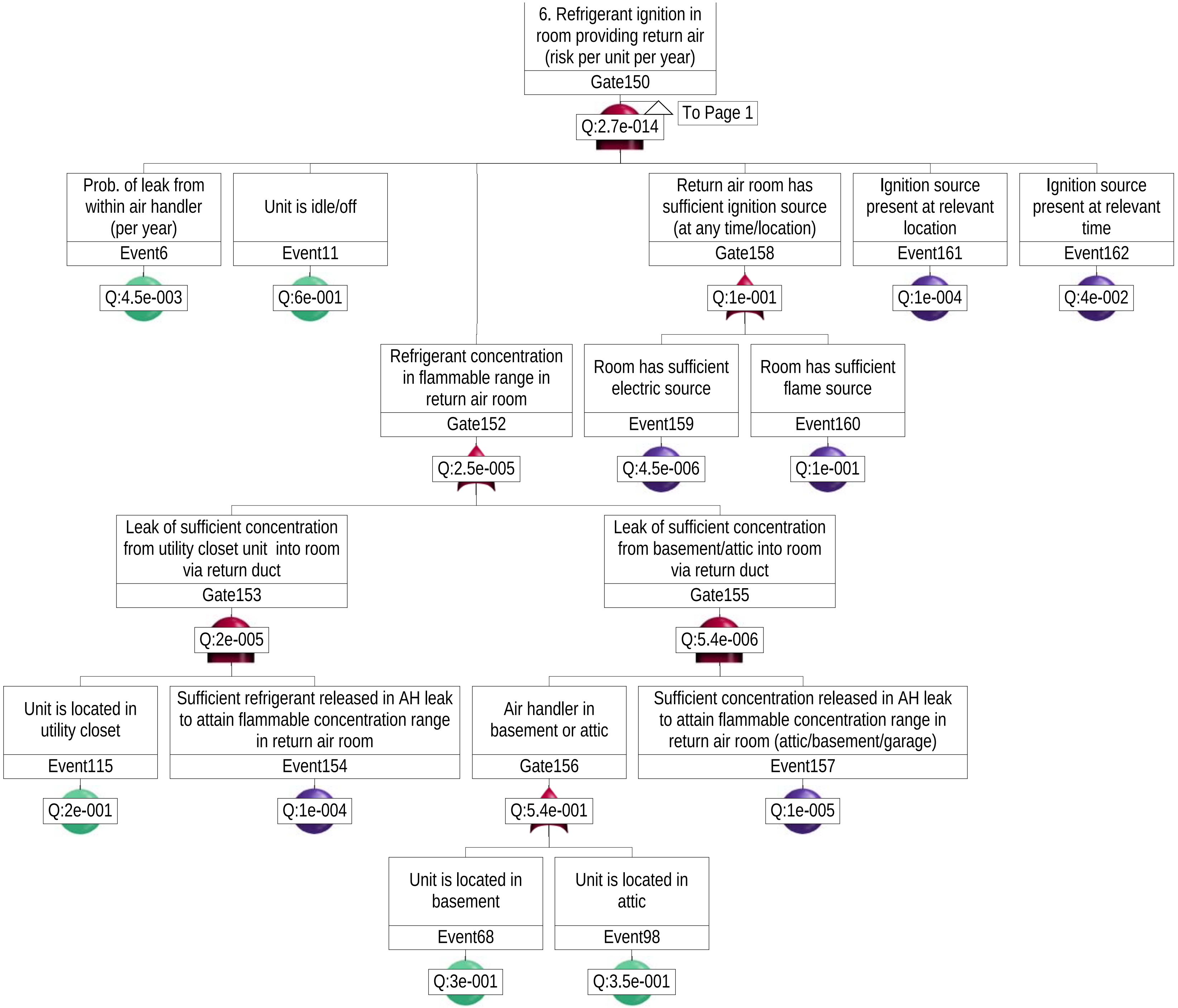

1. Refrigerant ignition due to leak in garage (risk per unit per year)
Gate2
Q:1e-012
To Page 1
Refrigerant leaked into garage is ignited
Gate3
Q:6.8e-012
Unit is located in garage
Event45
Q:1.5e-001
Leak disperses into garage and is in flammable range
Gate4
Q:5.6e-006
Sufficient ignition source present in garage to ignite refrigerant
Gate26
Q:1.2e-006
Refrigerant is in flammable concentration range in garage (air handler leak)
Gate5
Q:5.4e-006
Refrigerant is in flammable concentration range in garage (piping leak)
Gate17
Q:1.8e-007
Sufficient electrical source present in garage
Gate27
Q:1e-006
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Refrigerant in flammable concentration range after air hand. leak
Gate7
Q:1.2e-003
Prob. of leak from inlet piping to air handler (per year)
Event18
Q:1e-004
Refrigerant in flammable concentration range after inlet piping leak
Gate19
Q:1.8e-003
HVAC spark source of sufficient energy present in garage
Gate28
Q:1e-006
Sufficient flame source present in garage
Gate41
Q:2.3e-007
Sufficient refr release to attain flammable conc range in garage, air hand leak
Event9
Q:2e-003
Unit is idle/off
Event11
Q:6e-001
Sufficient refr release to attain flammable conc range in garage, inlet piping leak
Event21
Q:3e-003
Unit is idle/off
Event11
Q:6e-001
HVAC associated sparks present
Gate29
Q:2.5e-001
HVAC-related spark present at correct place
Event32
Q:1e+000
HVAC-related spark present at correct time
Event33
Q:4e-006
Non-HVAC source of sufficient energy present in garage
Gate35
Q:2.3e-011
Flame source present in garage
Event42
Q:4.5e-003
Flame source in garage present at correct place
Event43
Q:1e-003
Flame source in garage present at correct time
Event44
Q:5e-002
Electrostatic air cleaner spark occurs of sufficient energy
Event30
Q:0e+000
HVAC electronic-related spark occurs of sufficient energy
Event31
Q:2.5e-001
Non-HVAC related spark occurs in garage of sufficient energy
Event36
Q:1e-004
Non-HVAC spark in garage present at correct place
Event37
Q:1e-003
Non-HVAC spark in garage present at correct time
Event38
Q:2.3e-004

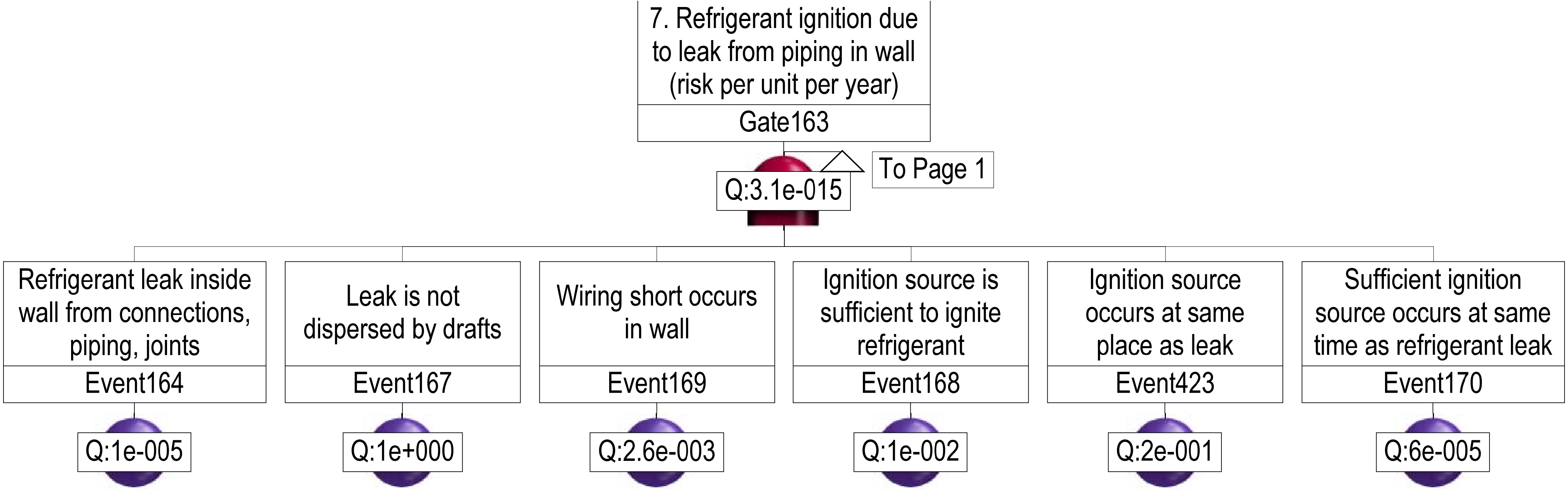

2. Refrigerant ignition due to leak in basement (risk per unit per year)
Gate47
Q:2.4e-012
To Page 1
Refrigerant leaked into basement is ignited
Gate48
Q:8.1e-012
Unit is located in basement
Event68
Q:3e-001
Leak disperses into basement and is in flammable range
Gate49
Q:5.6e-006
Refrigerant is in flammable concentration range in basement (AH leak)
Gate50
Q:5.4e-006
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Sufficient refr release to attain flammable conc range in basement, air hand leak
Event51
Q:2e-003
Unit is idle/off
Event11
Q:6e-001
Refrigerant is in flammable concentration range in basement (piping leak)
Gate52
Q:1.8e-007
Prob. of leak from inlet piping to air handler (per year)
Event18
Q:1e-004
Sufficient refr release to attain flammable conc range in basement, inlet piping leak
Event53
Q:3e-003
Unit is idle/off
Event11
Q:6e-001
Sufficient ignition source present in basement to ignite refrigerant
Gate54
Q:1.5e-006
Sufficient electrical source present in basement
Gate55
Q:1e-006
HVAC spark source of sufficient energy present in basement
Gate56
Q:1e-006
HVAC associated sparks present
Gate57
Q:2.5e-001
Electrostatic air cleaner spark occurs of sufficient energy
Event30
Q:0e+000
HVAC electronic-related spark occurs of sufficient energy
Event31
Q:2.5e-001
HVAC-related spark present at correct place
Event32
Q:1e+000
HVAC-related spark present at correct time
Event33
Q:4e-006
Non-HVAC source of sufficient energy present in basement
Gate59
Q:2.3e-011
Non-HVAC related sparks of sufficient energy in basement (e.g., owner activities)
Event60
Q:1e-004
Non-HVAC spark in basement present at correct place
Event62
Q:1e-003
Non-HVAC spark in basement present at correct time
Event61
Q:2.3e-004
Sufficient flame source present in basement
Gate64
Q:4.5e-007
Flame source present in basement sufficient to ignite refrigerant
Event65
Q:4.5e-003
Flame source in basement present at correct place
Event66
Q:1e-003
Flame source in basement present at correct time
Event67
Q:1e-001

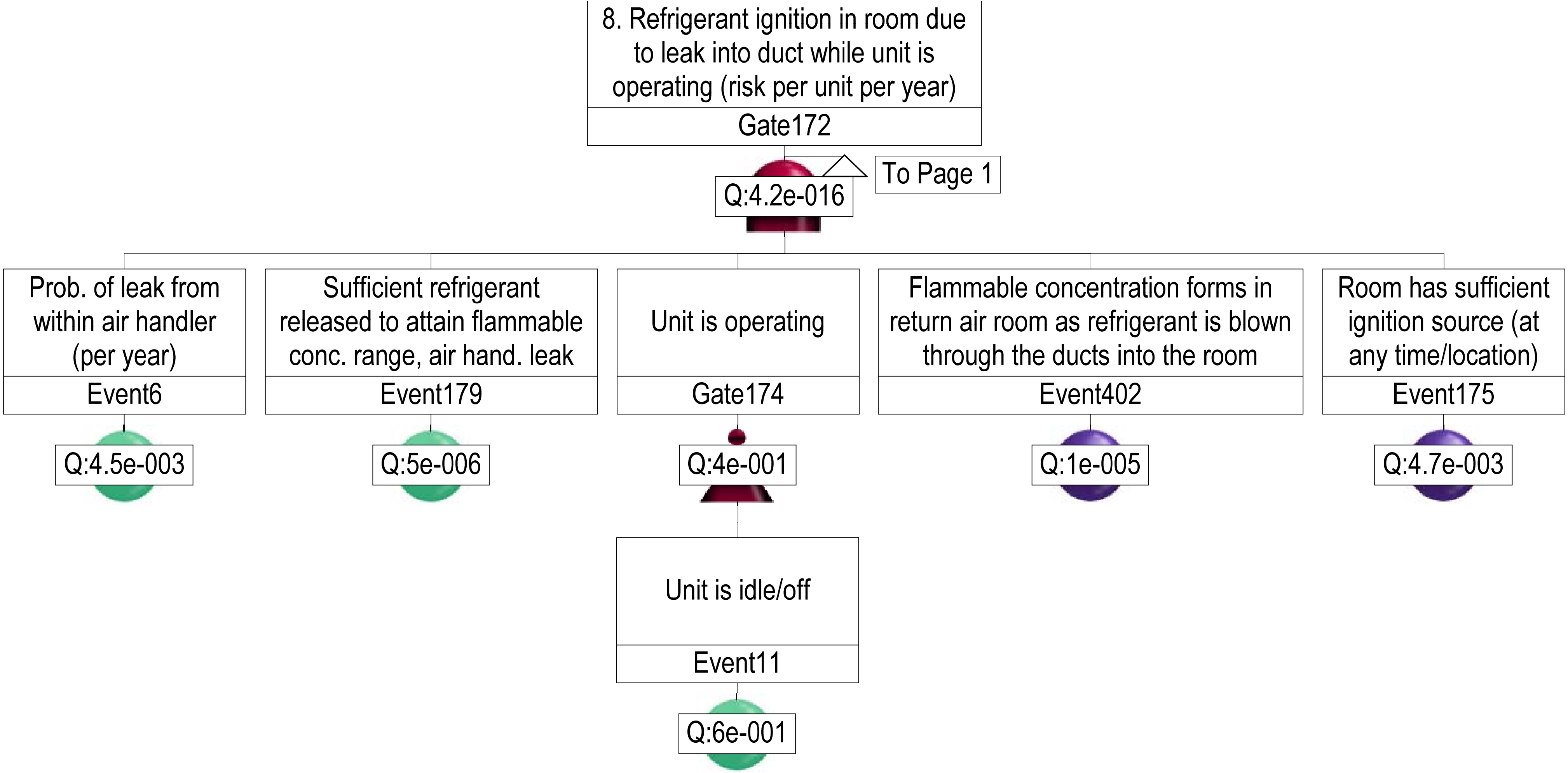

3. Refrigerant ignition due to leak in attic (risk per unit per year)
Gate69
Q:9.8e-013
To Page 1
Refrigerant leaked into attic is ignited
Gate70
Q:2.8e-012
Unit is located in attic
Event98
Q:3.5e-001
Leak disperses into attic and is in flammable range
Gate71
Q:2.8e-006
Sufficient ignition source present in attic to ignite refrigerant
Gate88
Q:1e-006
Refrigerant is in flammable concentration range in attic (piping leak)
Gate80
Q:9e-008
Sufficient electrical source present in attic
Gate89
Q:1e-006
Sufficient flame source present in attic
Event97
Q:0e+000
Refrigerant is in flammable concentration range in attic (AH leak)
Gate72
Q:2.7e-006
Prob. of leak from inlet piping to air handler (per year)
Event18
Q:1e-004
Refrigerant in flammable concentration range after inlet piping leak
Gate81
Q:9e-004
HVAC spark source of sufficient energy present in attic
Gate90
Q:1e-006
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Refrigerant in flammable concentration range after air hand. leak
Gate73
Q:6e-004
Sufficient refr release to attain flammable conc range in attic, inlet piping leak
Event83
Q:1.5e-003
Unit is idle/off
Event11
Q:6e-001
HVAC associated sparks present
Gate91
Q:2.5e-001
HVAC-related spark present at correct place
Event32
Q:1e+000
HVAC-related spark present at correct time
Event33
Q:4e-006
Non-HVAC source of sufficient energy present in attic
Gate93
Q:5.3e-015
Sufficient refr release to attain flammable conc range in attic, air hand leak
Event75
Q:1e-003
Unit is idle/off
Event11
Q:6e-001
Electrostatic air cleaner spark occurs of sufficient energy
Event30
Q:0e+000
HVAC electronic-related spark occurs of sufficient energy
Event31
Q:2.5e-001
Non-HVAC related sparks of sufficient energy in attic
Event94
Q:5.3e-004
Non-HVAC spark in attic present at correct place
Event95
Q:1e-006
Non-HVAC spark in attic present at correct time
Event96
Q:1e-005

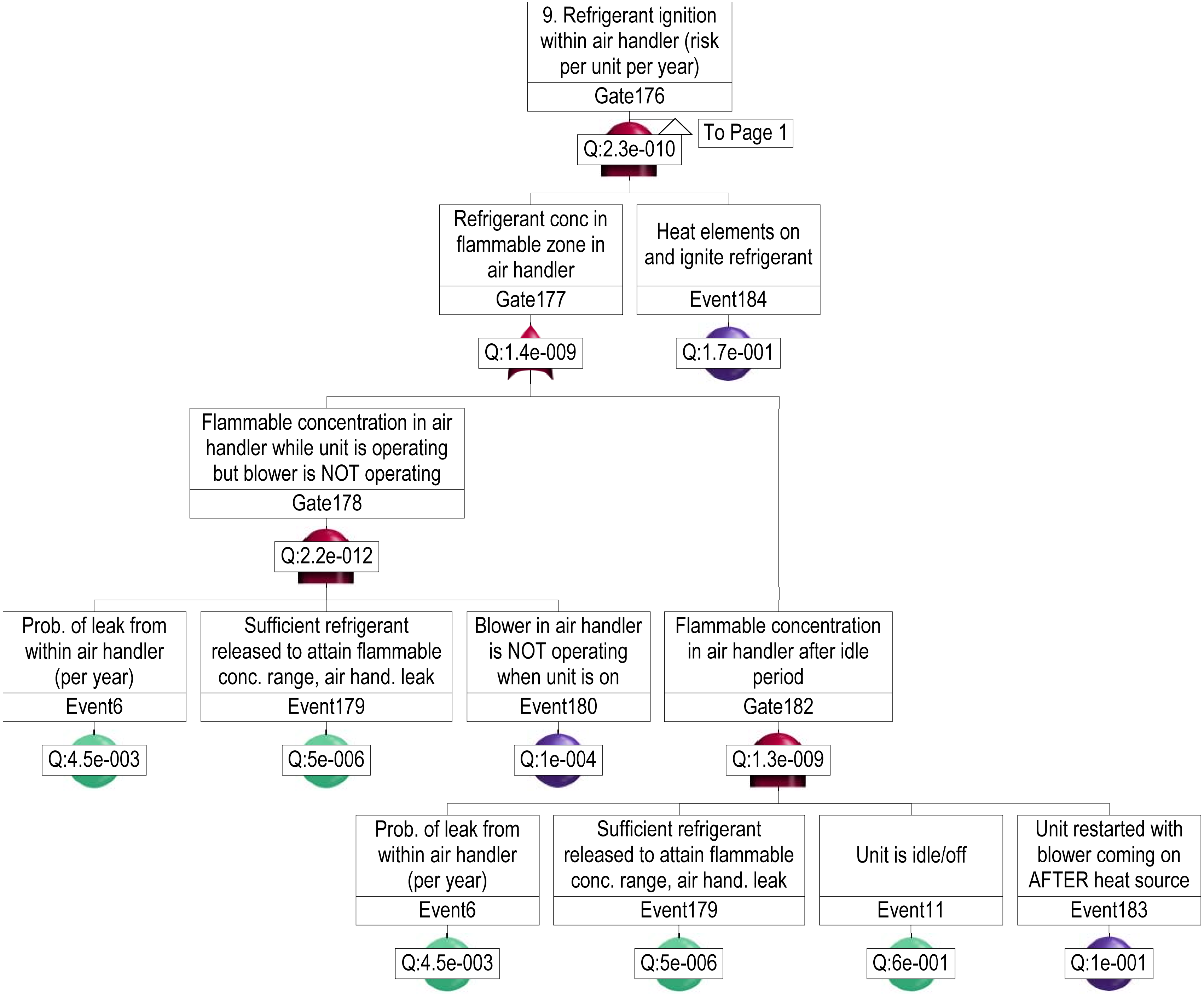

4. Refrigerant ignition due to leak in utility closet (risk per unit per year)
Gate100
Q:7.9e-009
To Page 1
Refrigerant leaked into utility closet is ignited
Gate101
Q:3.9e-008
Unit is located in utility closet
Event115
Q:2e-001
Leak disperses into utility closet and is in flammable range
Gate102
Q:2.8e-004
Sufficient ignition source present in utility closet to ignite refrigerant
Gate107
Q:1.4e-004
Refrigerant is in flammable concentration range in utility closet (piping leak)
Gate105
Q:9e-006
Refrigerant is in flammable concentration range in utility closet (AH leak)
Gate103
Q:2.7e-004
Prob. of leak from inlet piping to air handler (per year)
Event18
Q:1e-004
Unit is idle/off
Event11
Q:6e-001
HVAC spark source of sufficient energy present in utility closet
Gate108
Q:1e-006
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Unit is idle/off
Event11
Q:6e-001
Sufficient refr release to attain flammable conc range in utility closet, inlet piping leak
Event106
Q:1.5e-001
HVAC associated sparks present
Gate109
Q:2.5e-001
HVAC-related spark present at correct place
Event32
Q:1e+000
HVAC-related spark present at correct time
Event33
Q:4e-006
Sufficient flame source present in utility closet
Gate111
Q:1.4e-004
Sufficient refr release to attain flammable conc range in utility closet, air hand leak
Event104
Q:1e-001
Electrostatic air cleaner spark occurs of sufficient energy
Event30
Q:0e+000
HVAC electronic-related spark occurs of sufficient energy
Event31
Q:2.5e-001
Flame source present in utility closet
Event112
Q:5.6e-003
Flame source in utility closet present at correct place
Event113
Q:5e-001
Flame source in utility closet present at correct time
Event114
Q:5e-002

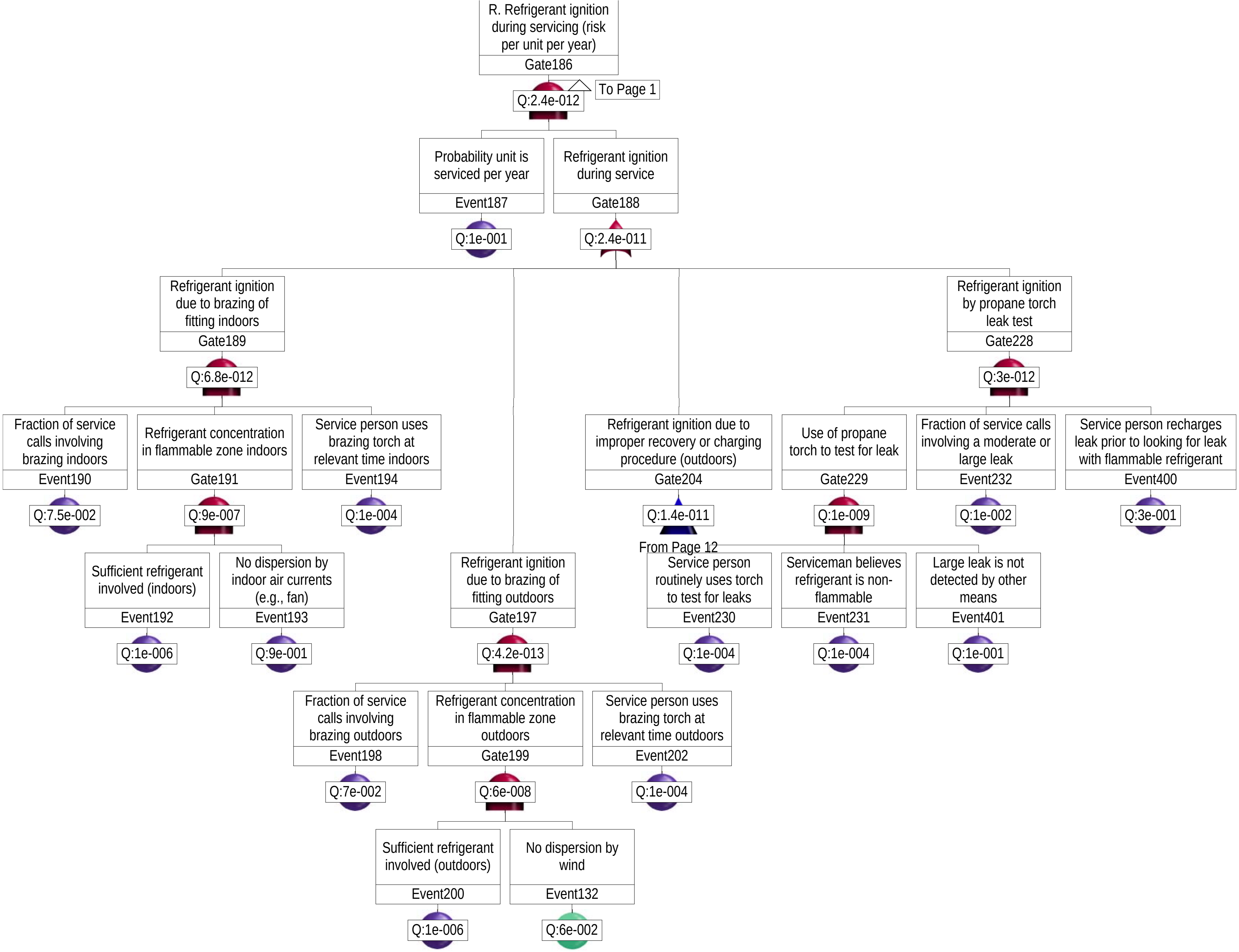

5. Refrigerant ignition due to leak outdoors (risk per unit per year)
Gate116
Q:1.8e-005
To Page 1
Ignition of leak within condensing unit (non-feed through plug)
Gate126
Q:2.1e-011
Ignition of leak within condensing unit (feed through plug)
Gate118
Q:1.8e-005
Leak from outdoor unit, other than feed through plug fault (per unit per year)
Event127
Q:4.5e-003
Refrigerant is in flammable concentration range
Gate128
Q:6.2e-001
Failure of electrical feed through plug (per unit, per year)
Event119
Q:9e-005
Leak is large enough to produce a flammable refrigerant concentration
Event120
Q:1e+000
Plug fault is of sufficient energy to ignite refrigerant
Event123
Q:1e+000
Release is not so turbulent as to quench refrigerant flame
Event125
Q:2e-001
Sufficient spark source present
Gate140
Q:7.5e-009
Leak is large enough to produce a flammable refrigerant concentration
Event120
Q:1e+000
No air flow through unit
Gate129
Q:6.2e-001
Spark produced by electrical controls during operation
Gate141
Q:7.5e-009
Unit is idle/off
Event11
Q:6e-001
No dispersion by wind
Event132
Q:6e-002
Spark due to fan motor fault
Gate146
Q:5.1e-014
Control system spark/arc occurs that is of sufficient energy
Event144
Q:2.5e-001
Box around electronics does not prevent flame propagation to rest of refrigerant
Event143
Q:1e-004
Control system spark occurs at relevant time
Event396
Q:3e-004
Fault in fan motor
Event147
Q:1.8e-005
Fan spark is of sufficient energy
Event148
Q:9.5e-001
Case around fan motor does not prevent flame propagation to rest of refrigerant
Event393
Q:1e-005
Fan motor spark occurs at relevant time
Event397
Q:3e-004

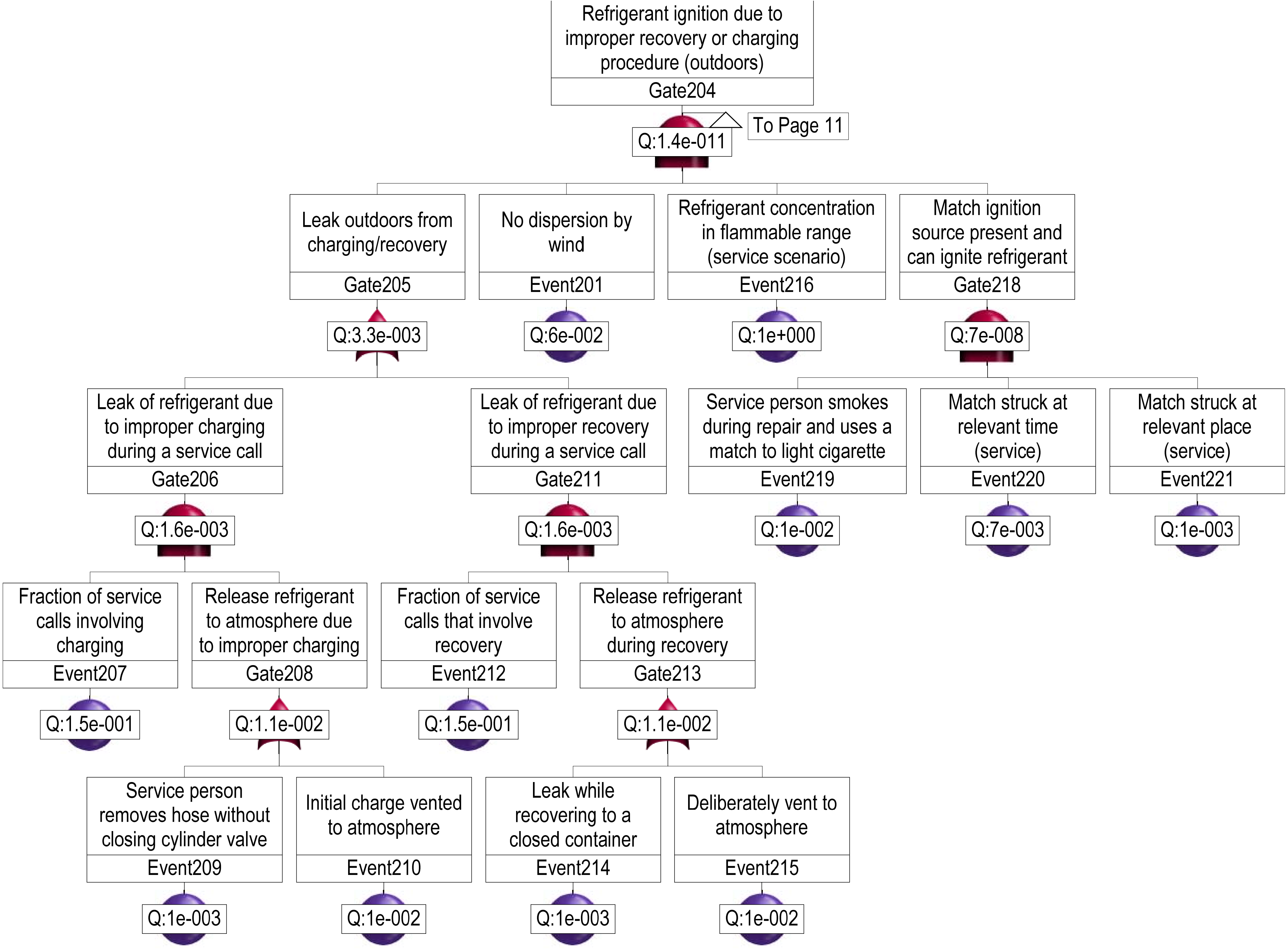

6. Refrigerant ignition in room providing return air (risk per unit per year)
Gate150
To Page 1
Q:2.7e-014
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Unit is idle/off
Event11
Q:6e-001
Return air room has sufficient ignition source (at any time/location)
Gate158
Q:1e-001
Ignition source present at relevant location
Event161
Q:1e-004
Ignition source present at relevant time
Event162
Q:4e-002
Refrigerant concentration in flammable range in return air room
Gate152
Q:2.5e-005
Room has sufficient electric source
Event159
Q:4.5e-006
Room has sufficient flame source
Event160
Q:1e-001
Leak of sufficient concentration from utility closet unit into room via return duct
Gate153
Q:2e-005
Leak of sufficient concentration from basement/attic into room via return duct
Gate155
Q:5.4e-006
Unit is located in utility closet
Event115
Q:2e-001
Sufficient refrigerant released in AH leak to attain flammable concentration range in return air room
Event154
Q:1e-004
Air handler in basement or attic
Gate156
Q:5.4e-001
Sufficient concentration released in AH leak to attain flammable concentration range in return air room (attic/basement/garage)
Event157
Q:1e-005
Unit is located in basement
Event68
Q:3e-001
Unit is located in attic
Event98
Q:3.5e-001


7. Refrigerant ignition due to leak from piping in wall (risk per unit per year)
Gate163
Q:3.1e-015
To Page 1
Refrigerant leak inside wall from connections, piping, joints
Event164
Q:1e-005
Leak is not dispersed by drafts
Event167
Q:1e+000
Wiring short occurs in wall
Event169
Q:2.6e-003
Ignition source is sufficient to ignite refrigerant
Event168
Q:1e-002
Ignition source occurs at same place as leak
Event423
Q:2e-001
Sufficient ignition source occurs at same time as refrigerant leak
Event170
Q:6e-005


8. Refrigerant ignition in room due to leak into duct while unit is operating (risk per unit per year)
Gate172
Q:4.2e-016
To Page 1
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Sufficient refrigerant released to attain flammable conc. range, air hand. leak
Event179
Q:5e-006
Unit is operating
Gate174
Q:4e-001
Flammable concentration forms in return air room as refrigerant is blown through the ducts into the room
Event402
Q:1e-005
Room has sufficient ignition source (at any time/location)
Event175
Q:4.7e-003
Unit is idle/off
Event11
Q:6e-001


9. Refrigerant ignition within air handler (risk per unit per year)
Gate176
Q:2.3e-010
To Page 1
Refrigerant conc in flammable zone in air handler
Gate177
Q:1.4e-009
Heat elements on and ignite refrigerant
Event184
Q:1.7e-001
Flammable concentration in air handler while unit is operating but blower is NOT operating
Gate178
Q:2.2e-012
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Sufficient refrigerant released to attain flammable conc. range, air hand. leak
Event179
Q:5e-006
Blower in air handler is NOT operating when unit is on
Event180
Q:1e-004
Flammable concentration in air handler after idle period
Gate182
Q:1.3e-009
Prob. of leak from within air handler (per year)
Event6
Q:4.5e-003
Sufficient refrigerant released to attain flammable conc. range, air hand. leak
Event179
Q:5e-006
Unit is idle/off
Event11
Q:6e-001
Unit restarted with blower coming on AFTER heat source
Event183
Q:1e-001


R. Refrigerant ignition during servicing (risk per unit per year)
Gate186
Q:2.4e-012
To Page 1
Probability unit is serviced per year
Event187
Q:1e-001
Refrigerant ignition during service
Gate188
Q:2.4e-011
Refrigerant ignition due to brazing of fitting indoors
Gate189
Q:6.8e-012
Refrigerant ignition by propane torch leak test
Gate228
Q:3e-012
Fraction of service calls involving brazing indoors
Event190
Q:7.5e-002
Refrigerant concentration in flammable zone indoors
Gate191
Q:9e-007
Service person uses brazing torch at relevant time indoors
Event194
Q:1e-004
Refrigerant ignition due to improper recovery or charging procedure (outdoors)
Gate204
Q:1.4e-011
From Page 12
Use of propane torch to test for leak
Gate229
Q:1e-009
Fraction of service calls involving a moderate or large leak
Event232
Q:1e-002
Service person recharges leak prior to looking for leak with flammable refrigerant
Event400
Q:3e-001
Sufficient refrigerant involved (indoors)
Event192
Q:1e-006
No dispersion by indoor air currents (e.g., fan)
Event193
Q:9e-001
Refrigerant ignition due to brazing of fitting outdoors
Gate197
Q:4.2e-013
Service person routinely uses torch to test for leaks
Event230
Q:1e-004
Serviceman believes refrigerant is non-flammable
Event231
Q:1e-004
Large leak is not detected by other means
Event401
Q:1e-001
Fraction of service calls involving brazing outdoors
Event198
Q:7e-002
Refrigerant concentration in flammable zone outdoors
Gate199
Q:6e-008
Service person uses brazing torch at relevant time outdoors
Event202
Q:1e-004
Sufficient refrigerant involved (outdoors)
Event200
Q:1e-006
No dispersion by wind
Event132
Q:6e-002


Refrigerant ignition due to improper recovery or charging procedure (outdoors)
Gate204
To Page 11
Q:1.4e-011
Leak outdoors from charging/recovery
Gate205
Q:3.3e-003
No dispersion by wind
Event201
Q:6e-002
Refrigerant concentration in flammable range (service scenario)
Event216
Q:1e+000
Match ignition source present and can ignite refrigerant
Gate218
Q:7e-008
Leak of refrigerant due to improper charging during a service call
Gate206
Q:1.6e-003
Leak of refrigerant due to improper recovery during a service call
Gate211
Q:1.6e-003
Service person smokes during repair and uses a match to light cigarette
Event219
Q:1e-002
Match struck at relevant time (service)
Event220
Q:7e-003
Match struck at relevant place (service)
Event221
Q:1e-003
Fraction of service calls involving charging
Event207
Q:1.5e-001
Release refrigerant to atmosphere due to improper charging
Gate208
Q:1.1e-002
Fraction of service calls that involve recovery
Event212
Q:1.5e-001
Release refrigerant to atmosphere during recovery
Gate213
Q:1.1e-002
Service person removes hose without closing cylinder valve
Event209
Q:1e-003
Initial charge vented to atmosphere
Event210
Q:1e-002
Leak while recovering to a closed container
Event214
Q:1e-003
Deliberately vent to atmosphere
Event215
Q:1e-002