AHRI Project 8009 Final Report

Risk Assessment of Refrigeration Systems Using A2L Flammable Refrigerants

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Abbreviations

AEGL	Acute Exposure Guideline Level
AHRI	Air-Conditioning, Heating and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
CFD	Computational Fluid Dynamics
FT	Fault Tree
FTA	Fault Tree Analysis
GWP	Global Warming Potential
HF	Hydrogen Fluoride
HVAC	Heating, Ventilating, and Air Conditioning
LFL	Lower Flammable Limit
MIE	Minimum Ignition Energy
ODP	Ozone Depletion Potential
OEM	Original Equipment Manufacturer
R-1234yf	2,3,3,3-Tetrafluoropropene
R-1234ze(E)	trans-1,1,1,3-Tetrafluoropropene
R-125	Pentafluoroethane
R-134a	1,1,1,2-Tetrofluoroethane
R-143a	1,1,1-Trifluoroethane
R-22	Chlorodifluoromethane
R-32	1,1-Difluoromethane
RIAC	Reliability Information Analysis Center
RSD	Relative Standard Deviation
SI	International System of Units
THC	Total Hydrocarbon
UFL	Upper Flammable Limit
US DoD	United States Department of Defense
US NRC	United States Nuclear Regulatory Commission

Executive Summary

There is currently world-wide interest in developing substitutes for materials whose environmental release may contribute to global climate change. The primary refrigerants used in commercial reach-in and walk-in coolers are R-404A and R-134a, greenhouse gases with global warming potentials (GWPs) in excess of 1,400. Possible replacements for these refrigerants in commercial applications include ASHRAE Class 2L refrigerants, which have lower global warming potentials but are mildly flammable. Although normal operation poses negligible risk, accidental releases due to equipment fault or fatigue could potentially result in refrigerant ignition if a sufficient ignition source is also present at the time and location of the release. To better understand 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 commercial cooler systems. Three location scenarios were evaluated: a small restaurant kitchen, a lunch counter, and a convenience store. Two types of units were studied: walk-in and reach-in coolers. The work included Computational Fluid Dynamics (CFD) modeling, experimental measurements, and a fault tree analysis (FTA) to quantify ignition risks. The CFD modeling indicated that for large accidental releases of R-32, R-1234yf, and R-1234ze(E) (*i.e.*, on the order of 50 g/s for R-32, 25 g/s for R-1234yf and 1234-ze(E)), refrigerant concentrations in a small restaurant kitchen, lunch counter, and convenience store can be expected to be substantially below their respective lower flammable limits (LFLs). Incorporating these findings, the FTA estimated that the risks of refrigerant ignition due to an accidental refrigerant leak across the different scenarios ranged from 10^{-10} to 10^{-13} events per unit per year for R-1234ze(E), from 10^{-9} to 10^{-12} events per unit per year for R-1234yf, and from 10^{-9} to 10^{-11} events per unit per year for R-32. For comparison, the overall risk of a significant commercial structure fire in the US is 2×10^{-2} per structure per year. The FTA-estimated risks were driven by the kitchen walk-in cooler scenario, which involved the smallest air volumes and the greatest likelihood of a flame source being present (*i.e.*, a gas cook-top burner or pilot light). Risks for R-32 and R-1234yf were similar, because both are equally capable of being ignited by a flame source that might be found in a restaurant kitchen. Risks for R-1234ze(E) were lower because this refrigerant is only flammable at temperatures above normal room temperature. Based on CFD modeling, experimental testing, and FTA, the risk assessment indicates that average risks associated with the use 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.

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 in commercial reach-in and walk-in cooler applications – beginning in 1996. As a result of this action, most newly manufactured reach-in and walk-in coolers in the United States use R-134a or R-404A as their refrigerants (US EPA, 2010a). R-134a (1,1,1,2-tetrofluoroethane) has an ozone depletion potential (ODP) of 0 but has a global warming potential (GWP) of 1,430 (IPCC, 2007).[1] R-404A is a blend of 44% R-125 (pentafluoroethane), 52% R-143a (1,1,1-trifluoroethane), and R-134a. It has an ODP of 0 but a GWP of 3,922 (US EPA, 2010a). 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.*, American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE]-34/ISO-817 Class 2L). These refrigerants would provide a significant environmental benefit if they could be successfully adopted for use in stationary refrigeration applications (Powell, 2011). One low-GWP 2L refrigerant, R-1234yf (2,3,3,3-tetrafluoropropene), has been identified as suitable for use in automotive air conditioning (Gradient, 2009; US EPA, 2011), but significant differences between automotive and commercial reach-in and walk-in cooler systems preclude direct extrapolation between these uses. An earlier evaluation of R-152a (a Class 2 refrigerant) for use in home refrigerators (ADL, 1991) reported a low risk of fire or explosion – less than one fire per million refrigerators per year from leaks during operation and system service. While informative, the ADL study was conducted more than two decades ago and may not reflect current technologies or procedures, particularly for non-residential refrigeration systems using ASHRAE 2L refrigerants. More recently, Colbourne and Suen (2004) described a risk assessment of R-290, R-600a, and R-1270 in small indoor refrigeration systems, determining that a fire could occur up to 82 times per million refrigeration units per year. However, this risk assessment only considered refrigerants of class 3 rather than the 2L refrigerants of interest here which may pose lower flammability risks. 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 commercial cooler applications, given current technologies.

As used in the context of this evaluation, "risk" is the likelihood or probability that leaked refrigerant from a commercial reach-in or walk-in cooler 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 are 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.

[1] Measured relative to CO_2 and based on a 100-year time horizon.

2. An assessment of potential refrigerant concentrations in air in the event of an accidental refrigerant release in three different commercial locations – a kitchen in a small restaurant, a lunch counter, and a convenience store. Computational Fluid Dynamics (CFD) modeling and confirmatory experiments were used to evaluate potential concentrations.

3. 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 commercial reach-in and walk-in cooler systems and system failure mechanisms.

4. 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 ignition-related risks.

2 Properties of Alternative Refrigerants Under Study

The risk assessment evaluated three refrigerants: R-1234yf, R-1234ze(E) (trans-1,1,1,3-tetrafluoropropene), and R-32 (1,1-difluoromethane). R-1234yf and R-1234ze(E) are newer 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 those of R-134a and R-404A (US EPA, 2010a,b; 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-134a and 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 commercial walk-in and reach-in cooler applications. The GWP of R-32 is 675 (US EPA, 2010c).

Table 2.1 summarizes the flammability properties of the refrigerants under study along with flammability properties for two other flammable gases which are also used as refrigerants: propane and ammonia. Testing according to American Society for Testing and Materials (ASTM) E-681-04 indicates that R-1234yf is flammable at room temperature (*i.e.*, 21°C or 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 for R-1234ze(E) is 7.0% and the UFL is 9.5% (Honeywell, 2008a). Humidity (*i.e.*, absolute humidity) may also modify the exact LFL for R-1234ze(E) (*i.e.*, it exhibits a slightly lower LFL at high humidity). R-32 is flammable at room temperature, although its 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 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 of 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, 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

[2] International System of Units (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.

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 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-134a and R-404A, the refrigerants currently used in commercial reach-in and walk-in coolers.

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[a]	14.4	2.2	15
Upper Flammable Limit (% volume in air)	12.3	9.5[a]	29.3	10	28
Minimum Ignition Energy (mJ)	5,000 to 10,000	61,000 to 64,000[b]	30 to 100	0.25	100 to 300
Burning velocity (cm/s)	1.5	0[c]	6.7	46	7.2
ASHRAE Safety Classification[d]	2L	2L	2L	3	2L

Notes:
ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers; R-1234yf = 2,3,3,3-Tetrafluoropropene; R-1234ze(E) = Trans-1,1,1,3-Tetrafluoropropene; R-32 = 1,1-Difluoromethane.
All data taken from Minor and Spatz (2008) unless otherwise indicated.
(a) R-1234ze(E) is not flammable at ambient temperatures; the data shown were obtained at 30°C.
(b) R-1234ze(E) is not flammable at ambient temperatures; the data shown were obtained at 54°C.
(c) Cannot be measured (*i.e.*, non-flammable) in the standard test.
(d) ASHRAE Standard 34 (2010)

Table 2.2 Toxicity Data for Refrigerants Under Study and Comparison Chemicals[a]

Endpoint	R-1234yf	R-1234ze(E)	R-32	R-134a	R-404A
Acute (LC50) (ppm)	> 406,000	> 207,000	> 760,000	359,000[b]	178,000[b]
Anesthetic Effects (ppm)	201,000	> 207,000	250,000	81,000[b]	300,000[b]
Cardiac Sensitization No Effect Level (ppm)	> 120,000	> 120,000	> 200,000	49,800[b]	126,000[b]
Worker Exposure Limit (ppm)	500[c]	800[d]	1,000[e]	1,000[f]	1000[h]
90-day NOAEL (ppm)	50,000[c]	5,000[d]	50,000[e]	50,000[f]	40,000[i]
Genotoxicity	Negative[c]	Negative[d]	Negative[e]	Negative[f]	Negative[h]
ASHRAE ATEL (ppm)	101,000	59,000	200,000	50,000[b]	130,000[b]

Notes:
ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers; ATEL = Acute-Toxicity Exposure Limit; LC50 = Lethal Concentration, 50 Percent; NOAEL = No Observed Adverse Effect Level; ppm = Parts per Million; R-1234yf = 2,3,3,3-Tetrafluoropropene; R-1234ze(E) = Trans-1,1,1,3-Tetrafluoropropene; R-32 = 1,1-Difluoromethane; RCL = Refrigerant Concentration Limit.
> = Effect was not observed at the highest concentration tested.
(a) Taken from Table E-1, ASHRAE Standard 34 (ASHRAE, 2010) unless otherwise noted.
(b) ASHRAE Standard 34 ATEL/RCL Calculation Spreadsheet (ASHRAE, 2013).
(c) DuPont (2011); Minor and Spatz (2008).
(d) Honeywell (2008b).
(e) ECETOC (2008).
(f) US EPA (2010d).
(g) ASHRAE Standard 34 (ASHRAE, 2010).
(h) Arkema Inc. (2009).
(i) Honeywell (2014). Lowest NOAEL of mixture component was used.

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 (*i.e.*, a worker, repair person or customer) at the time of the release. It is important to note that, during normal operations, the refrigerant will be contained within the commercial reach-in or walk-in cooler 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 (PMS) members, a number of scenarios were developed for evaluation as summarized below.

Table 3.1 Scenarios Considered in Risk Assessment

Leak Type/Equipment	Location
Large (rupture) and small (corrosion-induced) leaks in a self-contained reach-in cooler located in:	A convenience store. A kitchen in a small restaurant. A lunch counter.
Large (rupture) and small (corrosion-induced) leaks in a self-contained walk-in cooler located in:	A convenience store. A kitchen in a small restaurant.
Large (rupture) and small (corrosion-induced) leaks in a single condensing unit located outdoors and connected to:	A walk-in cooler in a convenience store. A walk-in cooler associated with a kitchen in a small restaurant.

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 CFD Modeling

To support the risk assessment, we conducted air dispersion modeling to determine whether leaked refrigerant would attain flammable concentrations in several commercial reach-in and walk-in cooler systems. Due to funding limitations, not all of the scenarios listed in Table 3.1 were selected for modeling (all were addressed in the fault tree analysis). We did not conduct CFD modeling of a release for a walk-in cooler in a convenience store. A release from a reach-in cooler in a convenience store was considered a more critical scenario because essentially all convenience stores will have a reach-in cooler, but not all convenience stores will have a walk-in cooler. Further, the walk-in cooler in a small kitchen (which was studied *via* CFD modeling) provides an indication of the risks associated with a walk-in cooler in a convenience store, the latter typically have a larger room volume. We also did not conduct

CFD modeling of a release for a reach-in cooler in a restaurant. The walk-in cooler in a small restaurant kitchen has a larger refrigerant charge than a reach-in cooler and represents the more conservative risk assessment of those two scenarios. The scenarios evaluated *via* CFD modeling are shown in Table 3.2.

Table 3.2 CFD Simulations Performed by GexCon

Initial Simulations	Orifice Sizes	Charge Size
Kitchen in a small restaurant, with the door to the walk-in cooler closed.	9.5 mm, 1.6 mm	4.5 kg
Kitchen in a small restaurant, with the door to the walk-in cooler open.	9.5 mm, 1.6 mm	4.5 kg
Lunch counter.	9.5 mm	0.91 kg
Convenience store.	9.5 mm	2.3 kg
Outdoor condenser with 85% porosity.	9.5 mm	4.5 kg
Exploratory Simulations		
Outdoor condenser with 50% porosity.	9.5 mm	4.5 kg
Outdoor condenser with 50% porosity in 10' by 10' enclosure.	9.5 mm	4.5 kg
Kitchen in a small restaurant, with the door to the walk-in cooler open with 800 cfm air flow.	9.5 mm	4.5 kg
Kitchen in a small restaurant, with the door to the walk-in cooler open with reduced leak pressure.	1.6 mm	4.5 kg

Notes:
CFD = Computational Fluid Dynamics; R-1234ze(E) = Trans-1,1,1,3-Tetrafluoropropene; R-32 = 1,1-Difluoromethane.
All simulations were conducted for both R-32 and R-1234ze(E)

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* 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 kitchen in a small restaurant, a lunch counter, and a convenience store (precise dimensions given in Figures 3.1 to 3.3). Appropriate furniture, shelves or other objects were placed in each of the commercial spaces to create realistic air volumes in each scenario. Air flow between rooms was passive (*i.e.*, heating, ventilating, and air conditioning [HVAC] system off) and driven largely by the air currents generated by the refrigerant releases. This approach is conservative for evaluating flammable concentrations, since air flow will tend to disperse the refrigerants and prevent high concentration build-up.

GexCon conducted a large number of modeling runs consistent with the initial simulations outlined in Table 3.2. Simulations included releases of R-32 and R-1234ze(E) through both small and large piping, using the release rates attained in the experimental study described in Section 3.3. The refrigerant was released from differing heights, depending on the simulation: releases occurred at a height of 2.1 m (7 ft) above the floor for reach-in cabinets (the top of the cabinet), releases for the walk-in cooler occurred from a height of 1.8 m (6 ft) above the floor, and releases for the condenser occurred near the floor. Based on prior CFD results, simulations for R-1234yf were expected to be nearly identical to results for R-1234ze(E), so the latter refrigerant was used for all simulations. The charge size varied among release scenarios between 0.91 kg (2 lb), 2.3 kg (5 lb), and 4.5 kg (10 lb), as shown in Table 3.2. 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.

Once the simulations of the initial scenarios described above were complete, we requested that GexCon conduct a number of exploratory simulations to see how changes in particular variables (*e.g.*, extent of enclosure, changes in airflow) might affect the CFD results. The prioritization of these exploratory simulations was discussed with and approved by the AHRI PMS subcommittee. The exploratory scenarios are also described in Table 3.2.

The CFD modeling provided two types of output: 1) videos showing 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. 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 0.65 m heights. Exact concentrations were tracked at up to seven variable height locations in each scenario, where specific ignition sources might be located (*e.g.*, wall sockets, countertop appliances, individuals lighting a cigarette).

Tables 3.3 to 3.5 summarize the results of the testing, and plots of refrigerant concentration over time for each scenario are shown in Figures 3.4 through 3.15. Screenshots from select video simulations are presented in Figures 3.16 through 3.20.

Examination of the CFD videos indicated that, in all of the scenarios, 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 (this is apparent in the videos but not in the plots, because there were no data tracking points in this area). Beyond this limited area, the scenario producing the highest concentrations (but well below the LFL) was the kitchen walk-in cooler with the door closed and a large (9.5 mm) leak. In this scenario released R-32 concentrations rose steadily until they reached a uniformly mixed condition at half the LFL for R-32 (Figure 3.4). The corresponding CFD simulation (Figure 3.16) shows the migration of the high concentration plume from in front of the release to the back of the cooler. Similarly for R-1234ze(E), the maximum concentration reached was 3.4%, roughly half the LFL for R-1234yf and less than half the LFL of R-1234ze(E) (at temperatures above 30ºC) (Figure 3.5). When the leak size was decreased to 1.6 mm, modeling suggested that R-32 concentrations in the cooler would not exceed 7% and R-1234ze(E) concentrations would not exceed 3.5% (Figures 3.6 and 3.7). In the cooler door open scenarios for the restaurant kitchen, R-32 concentrations never exceeded 3.5%, and R-1234ze(E) concentrations never exceeded 1.5% (Figures 3.8 to 3.11) because the released refrigerant mixes over the entire volume of the walk-in cooler and the kitchen relatively evenly (Figure 3.17). In the lunch counter and the convenience store scenarios, concentrations of R-32 were at or below 0.6% while those of R-1234ze(E) were at or below 0.3% (Figures 3.12 to 3.15). 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. The plumes resulting from the release in the lunch counter and convenience store are shown in Figures 3.18 and 3.19, respectively. It should be noted that the low burning velocity of these refrigerants makes it questionable whether a flame even in the small area directly in front of the leak could be sustained given the turbulent air flow associated with the leak. Overall, the CFD modeling indicates no possibility of R-32 nor R-1234ze(E) ignition in the modeled scenarios, because the refrigerant is rapidly mixed and diluted in room air. Flammable concentrations would only be possible in a case where the spaces were so crowded with objects (*e.g.*, equipment, boxes of supplies) that the free air volume was severely reduced. Given that the spaces modeled were already fairly small and filled with a reasonable approximation of expected equipment/fixtures, this would have to be an extreme situation. This possibility was addressed *via* the fault tree analysis discussed in Section 4.

Modeling of the outdoor condenser showed that high concentrations just outside of the condenser box are possible, nearing 11% for R-32 and 5% for R-1234ze(E). In neither case did the refrigerant reach the LFL. In the exploratory scenarios, it was found that changing the box porosity from 80% to 50% had a minimal impact on the refrigerant dispersion patterns. Placing a 3 m by 3 m (10 ft by 10 ft) enclosure around the condenser allowed concentrations very near the respective LFLs for both refrigerants to be reached just outside of the condenser, but minimal concentrations of refrigerant were observed to escape the enclosure (Figure 3.20). For the exploratory kitchen scenario with increased airflow (walk-in cooler with door open), slightly higher refrigerant concentrations occurred in the kitchen area due to the induced air flow from the walk-in cooler, but concentrations were still well below the LFL. Consistently, concentrations in the walk-in cooler and seating area appeared to decrease slightly with the increased airflow. For the kitchen scenario with the reduced leak pressure (walk-in cooler with door open and a 1.6 mm leak size), refrigerant concentrations increased more slowly, but peak concentrations were similar to those conducted at higher pressure.

The findings of the CFD modeling can also be considered in the context of a study performed for ASHRAE by Navigant Consulting (ASHRAE/Navigant, 2012). That study used CFD modeling to evaluate two commercial refrigeration scenarios that are similar to those considered here: a release from the exterior top of a walk-in cooler (condenser leak) and a release from an ice making machine. In this study, the release from the walk-in cooler resulted in "high concentrations" described as being "close to the LFL, but not necessarily above it". The ASHRAE/Navigant report does not indicate the extent of the area of "high concentration" or whether this was close to the location of potential ignition sources. The release from the ice making machine did not produce these high concentrations.

In contrast to the Navigant results, none of the walk-in cooler scenarios evaluated in the current study produced flammable concentrations of refrigerant in the CFD modeling. The refrigerant charge released in both walk-in cooler simulations was the same (4.5 kg). One key difference between the earlier work and that conducted here is that the room where the walk-in unit was located was extremely small in the Navigant study, 2.4 m x 3.6 m x 2.3 m. This is smaller than our small kitchen space (5.1 m x 3.6 m x 2.4 m) and far smaller than the convenience store (10 m x 10 m 2.4 m). Yet both the simulated spaces evaluated here were considered to be at the lower end of what could be a plausible space from the standpoint of functionality. The Navigant study also consisted of a single small room with no possibility of passive airflow to adjoining spaces. In our study, the kitchen space located next to the cooler was connected *via* a double door to the main seating area. Refrigerant could flow out beneath the door into the much larger adjacent space.

Table 3.3 Monitoring Point Locations Used in CFD Modeling Simulations and Experiments

Simulation Monitoring Point Location & Description	Height (m)	Height (in)
Kitchen in a Small Restaurant		
1) Walk-in cooler (front)	1.5	60
2) Walk-in cooler (front)	1.5	60
3) Walk-in cooler (rear)	0.9	36
4) Walk-in cooler (rear)	0.9	36
5) Kitchen (south wall)	0.9	36
6) Kitchen (middle)	1.5	60
7) Kitchen (near doors)	0.9	36
8) Seating area	0.3	12
Lunch Counter		
1) Reach-in cooler	0.3	12
2) Reach-in cooler	1.5	60
3) South wall, on counter	1.4	54
4) Center of room	1.5	60
5) West wall (opposite leak)	1.4	54
6) North wall	0.9	36
7) East wall (behind leak)	0.9	36
8) South wall, socket height	0.3	12
Convenience Store		
1) Reach-in cooler	0.3	12
2) Reach-in cooler	1.5	60
3) Between store rows	0.3	12
4) South wall (opposite leak)	1.4	54
5) Southwest corner	0.3	12
6) West aisle	0.3	12
7) West wall, on counter	1.4	54
8) South wall, on counter	0.9	36

Notes:
CFD = Computational Fluid Dynamics.
Locations are the same as those used in the experimental study conducted by Hughes Associates.

Table 3.4 Summary of Results of CFD Modeling for R-32

Scenario (Leak Rate)	Time LFL Exceeded (s)	Maximum Conc. at Monitoring Points (%)	Time LFL Exceeded (s)	Comment
Basic Scenarios				
Restaurant Kitchen	0	3.32	0	Concentrations well below the LFL in all locations.
Lunch Counter	0	0.41	0	Concentrations well below the LFL in all locations.
Convenience Store	0	0.63	0	Concentrations well below the LFL in all locations.
Exploratory Scenarios				
Restaurant Kitchen (Walk-in Cooler Door Closed)	0	7.12	0	Concentrations well below the LFL in all locations.

Notes:
CFD = Computational Fluid Dynamics; LFL = Lowest Flammable Limit; R-32 = 1,1-Difluoromethane.

Table 3.5 Summary of Results of CFD Modeling for R-1234ze(E)

Scenario (Leak Rate)	Time LFL Exceeded (s)	Maximum Conc. at Monitoring Points (%)	Time LFL Exceeded (s)	Comment
Basic Scenarios				
Restaurant Kitchen	0	1.43	0	Concentrations well below the LFL in all locations.
Lunch Counter	0	0.31	0	Concentrations well below the LFL in all locations.
Convenience Store	0	0.30	0	Concentrations well below the LFL in all locations.
Exploratory Scenarios				
Restaurant Kitchen (Walk-in Cooler Door Closed)	0	3.38	0	Concentrations well below the LFL in all locations.

Notes:
CFD = Computational Fluid Dynamics; LFL = Lowest Flammable Limit; R-1234ze(E) = Trans-1,1,1,3-Tetrafluoropropene.

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 three commercial scenarios (a kitchen in a small restaurant, a lunch counter, and a convenience store), Hughes Associates constructed a 100 m^2 test enclosure that was subsequently modified to represent each of the three testing scenarios. The room dimensions and interior structures for the kitchen in a small restaurant, lunch counter, and convenience store were consistent with those used in the CFD modeling (Figures 3.1 to 3.3). The mock-up was constructed with gypsum wall board over a metal stud frame. It included a 2.4 m (8 ft) high acoustic tile suspended ceiling and a steel plate floor (with joints taped). The enclosure had two doors at opposite corners and four 1.2 x 2.4 m polycarbonate windows for observation; the doors and the sub-floor were sealed to prevent migration of the refrigerant out of the experimental area. 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, since, even without HVAC system operation, coolers have associated fans that create some airflow. Cardboard boxes, stacked and placed next to one another, were used to simulate the volumes occupied by counters, shelves, and appliances. (Figures 3.21 to 3.22). Metal cabinets were used to simulate the reach-in coolers during the convenience store and lunch counter tests.

In each test, a refrigerant charge equivalent to the amount used in the CFD modeling was released from the same location used in the CFD modeling. For the kitchen in a small restaurant scenario, 4.5 kg (10 lb) was discharged to represent the charge mass from a walk-in cooler. Leak size was varied in this scenario by fitting the tubing with different orifice sizes: 9.5 mm (3/8"), 3.2 mm (1/8"), and 1.6 mm (1/16"); the open end of the tubing was used to represent a 9.5 mm release. During the lunch counter scenario, 0.9 kg (2 lb) of refrigerant was discharged to represent the mass from a small 1- or 2- door reach-in cooler. One larger mass release of 2.3 kg (5 lb) was tested, and orifice sizes of both 3.2 mm and 9.5 mm diameter were evaluated. A total of 2.3 kg (5 lb) of refrigerant was discharged during the convenience store scenario, representing the charge mass from a larger 3- or 4-door reach-in cooler. Table 3.6 summarizes the experimental tests performed. The refrigerant was released from a nominal 12L cylinder with a 13.6 kg (30 lb) capacity *via* 95 mm copper tubing. The length of the tubing from cylinder to discharge point was approximately 15.2 m (504 ft).

Table 3.6 Experimental Conditions Used by Hughes Associates in Experimental Study

Scenario	Orifice Sizes	Charge Sizes	Test Numbers
Kitchen in a small restaurant	9.5, 3.2, and 1.6 mm	4.5 kg	1-6, 12-19
Lunch counter	9.5 and 3.2 mm	0.9 kg, 2.3 kg	7-11
Convenience store	9.5 mm	2.3 kg	20-21

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 2009 Gradient study which showed identical dispersion patterns for the two refrigerants). 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 refrigeration system dissolved in the oil and, thus, would not contribute to air concentrations in the surrounding room. 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 12 to 63 g/s while those for R-1234ze(E) ranged from 12 to 33 g/s. The range in release rates is explained by differences in refrigerant characteristics, charge sizes, and leak sizes as shown in Table 3.7 below.

Table 3.7 Release Rates for Different Test Scenarios

Charge Size (kg)	Orifice Size (mm)	Range of Release Rates (g/s)
0.91	3.2	12
0.91	9.5	14-15
2.3	9.5	22-29
4.5	1.6	22
4.5	3.2	R-1234ze(E): 23 R-32: 55
4.5	9.5	R-1234ze(E): 27-33 R-32: 64

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 (owned by Hughes Associates) 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 and thus minimizing air currents. Sampling locations were chosen for each scenario by considering the locations of possible ignition sources (*e.g.*, 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 21 releases were performed in total, starting with the restaurant scenario, moving to the lunch counter and finishing with the convenience store (*i.e.*, by sequentially removing walls and rearranging the simulated interior structures). Problems with the refrigerant release and sampling configuration were apparent in the first six experimental tests in the restaurant scenario; these tests were repeated and the original results were not used in the data evaluation.[3] Eight successful tests were performed for the restaurant scenario (five with R-1234ze(E), three with R-32), five tests were conducted for the lunch counter scenario (two with R-1234ze(E), three with R-32), and two tests were performed for the convenience store scenario (one with each refrigerant). Based on the results of the small and large leaks conducted in the restaurant and lunch counter scenarios, it was apparent that small leaks in the convenience store setting would produce concentrations at or below the instrument detection limit (approximately 0.2%) and far below the LFL. As a result, only large leaks were evaluated in this scenario.

Tables 3.8, 3.9, and 3.10 summarize the results of the experimental testing. The maximum refrigerant concentration did not exceed the LFL for R-32 and R-1234ze(E),[4] and the location of the highest concentration varied with each test (see Figures 3.23 to 3.35). Scenarios modeling the walk-in cooler achieved higher concentrations than the scenarios modeling the reach-in cooler, as expected. The highest concentration across all of the experiments was 3.2% for R-32 in the kitchen area (cooler door open) and 2.9% for R-1234ze(E) in the walk-in cooler when the door was closed (Figure 3.23). Excluding the experiment with the door closed, the highest R-1234ze(E) concentration was 1.7%. Concentrations at all locations, except Sample 8, reached their peak at the end of the release, which took less than 5 minutes in each experiment, then slowly declined.. Concentrations at sample point 8, which was placed in the dining room of the small restaurant scenario, steadily increased to a plateau throughout the 30-minute experiment. Concentrations in the lunch counter scenario (Figures 3.29 to 3.32) were at or below 0.5%. An additional lunch counter scenario involving release of a 2.3 kg R-32 charge resulted in a peak concentration of 1.2%, although concentrations were at or below 0.7% for most of the simulation (Figure 3.33). For the convenience store scenario (Figures 3.34 to 3.35) concentrations of R-32 were below 1% while those of R-1234ze(E) were below 0.5%. Greater detail concerning the work conducted at Hughes Associates is provided in Appendix A.

[3] Note that the original proposal specified 14 release tests total. With these repeated tests excluded, a total of 15 tests were actually conducted.
[4] That is, the LFL for R-1234ze(E) at temperatures above 30°C.

Table 3.8 Summary of Results of Experiments for R-32

Scenario	Time LFL Exceeded (s)	Maximum Conc. at Monitoring Points (%)	Time LFL Exceeded (s)	Comment
Basic Scenarios				
Restaurant Kitchen	0	2.78	0	Concentrations well below the LFL in all locations.
Lunch Counter	0	0.38	0	Concentrations well below the LFL in all locations.
Convenience Store	0	0.66	0	Concentrations well below the LFL in all locations.
Exploratory Scenarios				
Lunch Counter (2.3 kg charge)	0	1.2	0	Concentrations well below the LFL in all locations.

Notes:
LFL = Lowest Flammable Limit; R-32 = 1,1-Difluoromethane.

Table 3.9 Summary of Results of Experiments for R-1234ze(E)

Scenario	Time LFL Exceeded (s)	Maximum Conc. at Monitoring Points (%)	Time LFL Exceeded (s)	Comment
Basic Scenarios				
Small Restaurant Kitchen	0	3.21	0	Concentrations well below the LFL in all locations.
Lunch Counter	0	1.20	0	Concentrations well below the LFL in all locations.
Convenience Store	0	1.10	0	Concentrations well below the LFL in all locations.
Exploratory Scenarios				
Restaurant Kitchen (Cooler Door Closed)	0	2.92	0	Concentrations well below the LFL in all locations.

Notes:
LFL = Lowest Flammable Limit; R-1234ze(E) = Trans-1,1,1,3-Tetrafluoropropene.

Table 3.11 presents the results of reproducibility testing (*i.e.*, three R-1234ze(E) tests in the kitchen in a small restaurant scenario under identical conditions) and indicates the data were reproducible, with relative standard deviations (RSDs) (*i.e.*, 100×sd/mean) almost always less than twenty-five percent. The exception was the Sample Point 1 30-minute TWA, where a low mean concentration measurement (less than half that of any other sampling point) results in a higher RSD statistic. 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 3.36 to 3.41 show a comparison of the results of the CFD modeling to the concentrations measured by Hughes Associates. The comparisons included the peak concentration and the concentrations measured at 120 s. Note that the y-axis for each refrigerant is scaled to that refrigerant's LFL, the ultimate metric of interest. Hughes Associates 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. Differences in the peak concentration and maximum 5-minute time-weighted average for the kitchen in a small restaurant, lunch counter, and convenience store scenario averaged less than 0.5%, with the exception of the kitchen in a small restaurant scenario where the door to the walk-in cooler was closed. In this experiment, the door was not sealed well, so significant refrigerant gas was able to disperse out of the walk-in cooler and into the kitchen area. The CFD simulation featured a well-sealed door, and the resulting concentration differences between the kitchen measurement points and the walk-in cooler measurement points were much higher than in the comparable Hughes Associates experiment.

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 and 7% for R-1234ze(E) or 14.4% for R-32), the modest differences in concentrations observed between the modeling results and experimental data suggest that the CFD modeling do provide a sufficiently accurate representation of actual experimental conditions.

Table 3.10 Concentration Data Obtained During Experimental Testing Across All 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
Restaurant Kitchen Scenario							
Walk-in Cooler, In Front of Leak	1.5	60	NA/Dispersion	2.16%	0.90%	2.92%	0.65%
Walk-in Cooler, North of Leak	1.5	60	NA/Dispersion	2.44%	1.22%	2.60%	1.16%
Walk-in Cooler, Behind Leak	0.9	36	NA/Dispersion	2.63%	1.69%	2.78%	1.27%
Walk-in Cooler, South of Leak	0.9	36	NA/Dispersion	2.52%	1.72%	2.75%	1.72%
Kitchen, South Wall	0.9	36	Stove/Cooking Appliance	1.29%	0.76%	0.66%	0.75%
Kitchen, North Wall	1.5	60	Stove/Cooking Appliance	2.81%	0.81%	1.50%	0.79%
Kitchen, Near Exit	0.9	36	Stove/Cooking Appliance	3.21%	1.87%	1.69%	1.81%
Seating Area	0.3	12	Wall Socket Short	2.20%	1.43%	1.13%	1.43%
Lunch Counter Scenario							
Reach-in Cooler, North of Leak	0.3	12	NA/Dispersion	0.00%	0.00%	0.00%	0.00%
Reach-in Cooler, North of Leak	1.5	60	NA/Dispersion	0.81%	0.62%	0.16%	0.10%
South Wall	1.4	54	Countertop Appliances	0.42%	0.38%	0.23%	0.20%
Room Center	1.5	60	NA/Dispersion	1.20%	0.64%	0.34%	0.15%
West Wall	1.4	54	NA/Dispersion	0.34%	0.25%	0.09%	0.06%
North Wall	0.9	36	Wall Socket Wiring Short	0.65%	0.42%	0.25%	0.04%
East Wall	0.9	36	NA/Dispersion	0.47%	0.35%	0.20%	0.16%
South Wall	0.3	12	Wall Socket Wiring Short	1.10%	0.42%	0.38%	0.24%
Convenience Store Scenario							
Reach-in Cooler	0.3	12	NA/Dispersion	0.00%	0.00%	0.66%	0.23%
Reach-in Cooler	1.5	60	NA/Dispersion	0.68%	0.52%	0.08%	0.02%
Between Aisles	0.3	12	NA/Dispersion	0.45%	0.21%	0.42%	0.42%
South Wall	1.4	54	NA/Dispersion	0.71%	0.49%	0.14%	0.06%
Southwest Corner	0.3	12	Wall Socket Wiring Short	0.49%	0.44%	0.50%	0.42%
West End of Aisles	0.3	12	NA/Dispersion	0.65%	0.46%	0.50%	0.33%
West Wall	1.4	54	Wall Socket Wiring Short	0.45%	0.37%	0.10%	0.06%
East Wall	0.9	36	Customer Lighter	1.10%	0.75%	0.25%	0.01%

Notes:

R-1234ze(E) = Trans-1,1,1,3-Tetrafluoropropene; R-32 = 1,1-Difluoromethane.; TWA = Time-Weighted Average.

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

Table 3.11 Reproducibility of Experimental Testing Results (Restaurant Kitchen Setting)

Line & Description	Statistic	Test: R-1234ze(E), No Orifice			Mean	Standard Deviation	RSD
		14	15	16			
1) Walk-in Cooler-East-High	Maximum	0.93%	1.46%	1.20%	1.20%	0.27%	22.22%
	5-min Average	0.65%	0.74%	0.95%	0.78%	0.16%	20.23%
	30-min Average	0.13%	0.15%	0.25%	0.17%	0.06%	36.50%
2) Walk-in Cooler-High-West	Maximum	1.24%	1.20%	1.24%	1.23%	0.03%	2.12%
	5-min Average	1.09%	1.08%	1.07%	1.08%	0.01%	1.05%
	30-min Average	0.41%	0.41%	0.35%	0.39%	0.03%	7.56%
3) Walk-in Cooler-West	Maximum	0.93%	1.26%	1.38%	1.19%	0.23%	19.44%
	5-min Average	0.88%	1.20%	1.30%	1.12%	0.22%	19.50%
	30-min Average	0.53%	0.75%	0.74%	0.67%	0.12%	18.48%
4) Walk-in Cooler-South	Maximum	1.35%	1.23%	1.37%	1.3.2%	0.07%	5.61%
	5-min Average	1.29%	1.20%	1.29%	1.26%	0.05%	3.93%
	30-min Average	0.79%	0.74%	0.75%	0.76%	0.02%	3.24%
5) Kitchen-South	Maximum	0.64%	0.58%	0.66%	0.63%	0.04%	5.93%
	5-min Average	0.59%	0.55%	0.61%	0.59%	0.03%	5.00%
	30-min Average	0.34%	0.3.2%	0.35%	0.34%	0.02%	4.59%
6) Mid-Kitchen-High	Maximum	1.50%	1.50%	1.50%	1.50%	0.00%	0.00%
	5-min Average	1.13%	1.27%	1.18%	1.20%	0.07%	5.83%
	30-min Average	0.36%	0.50%	0.37%	0.41%	0.08%	19.63%
7) Kitchen-High-North	Maximum	1.68%	1.57%	1.69%	1.65%	0.07%	4.06%
	5-min Average	1.47%	1.38%	1.47%	1.44%	0.05%	3.52%
	30-min Average	0.87%	0.82%	0.82%	0.84%	0.03%	3.13%
8) Seating Area-Low	Maximum	1.13%	1.13%	1.01%	1.09%	0.07%	6.66%
	5-min Average	1.07%	1.10%	0.88%	1.02%	0.12%	11.67%
	30-min Average	0.80%	0.74%	0.66%	0.73%	0.07%	9.70%

Notes:
R-1234ze(E) = Trans-1,1,1,3-Tetrafluoropropene; RSD = Relative Standard Deviation.
Data shown are repeat tests using R-1234ze(E) and the kitchen in a small restaurant scenario set up.
RSD of < 20% is fairly good.

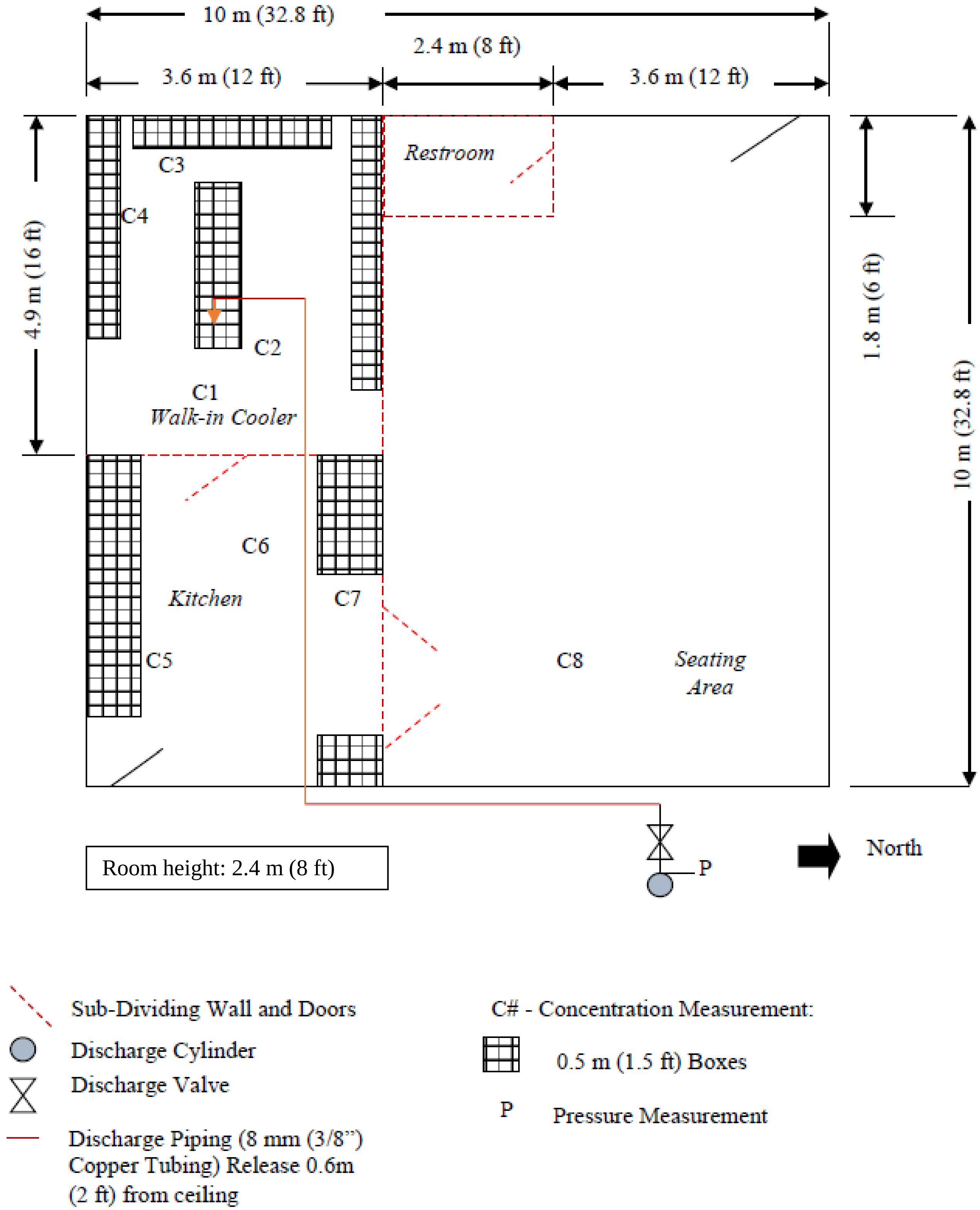


Figure 3.1 Schematic of Kitchen in a Small Restaurant (Café) Used for Experiments

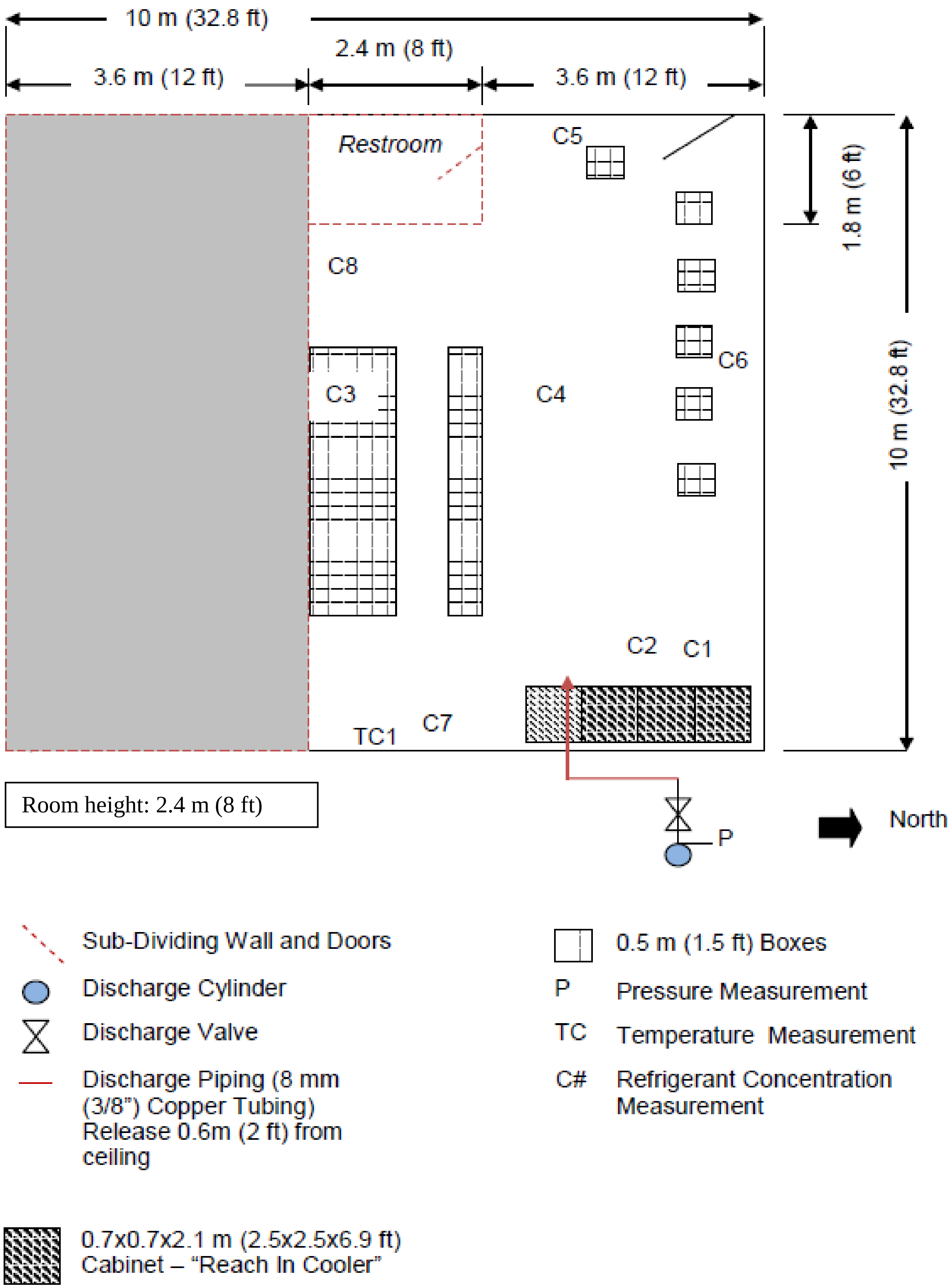


Figure 3.2 Schematic of Lunch Counter Used for Experiments

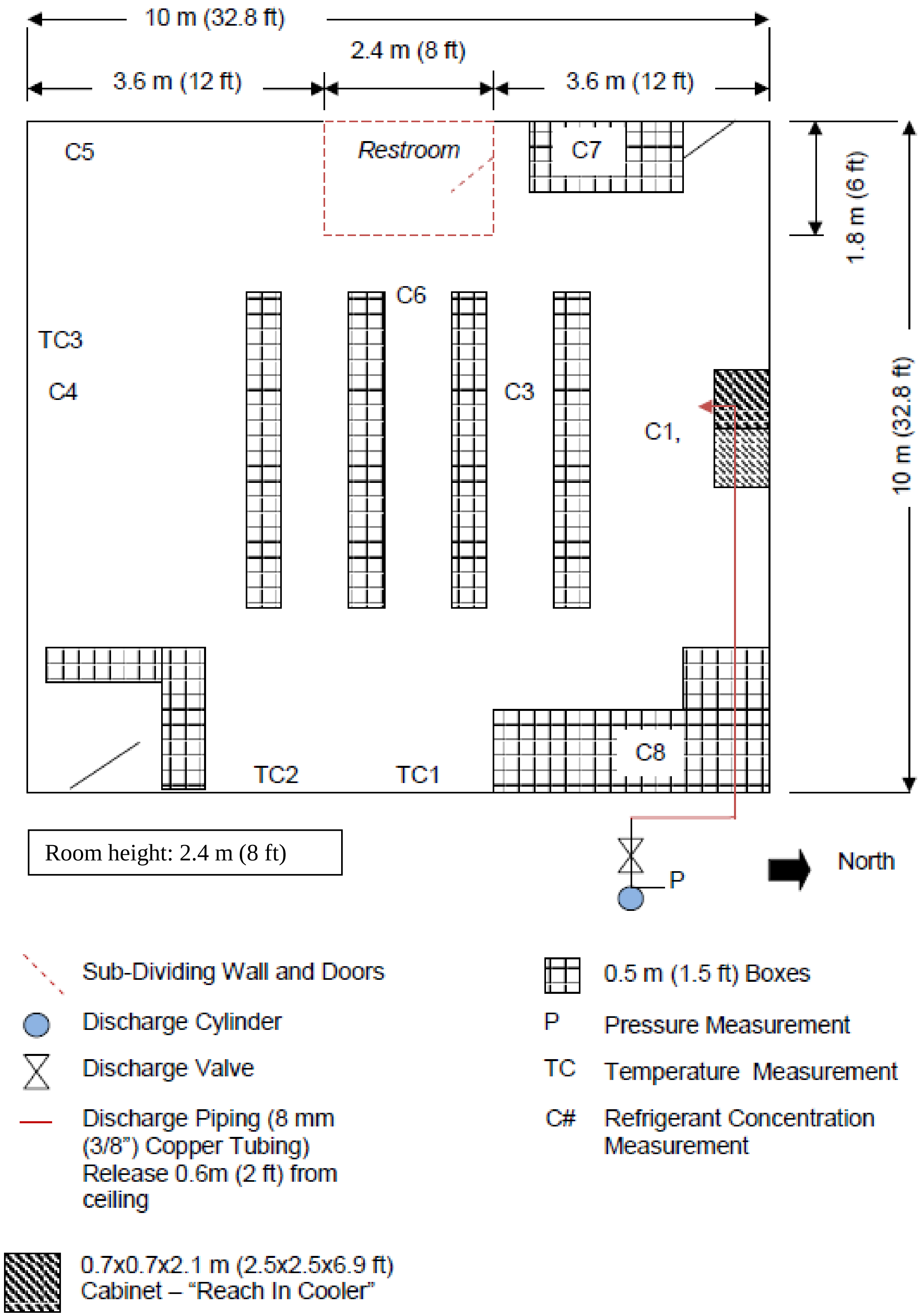


Figure 3.3 Schematic of Convenience Store Used for Experiments

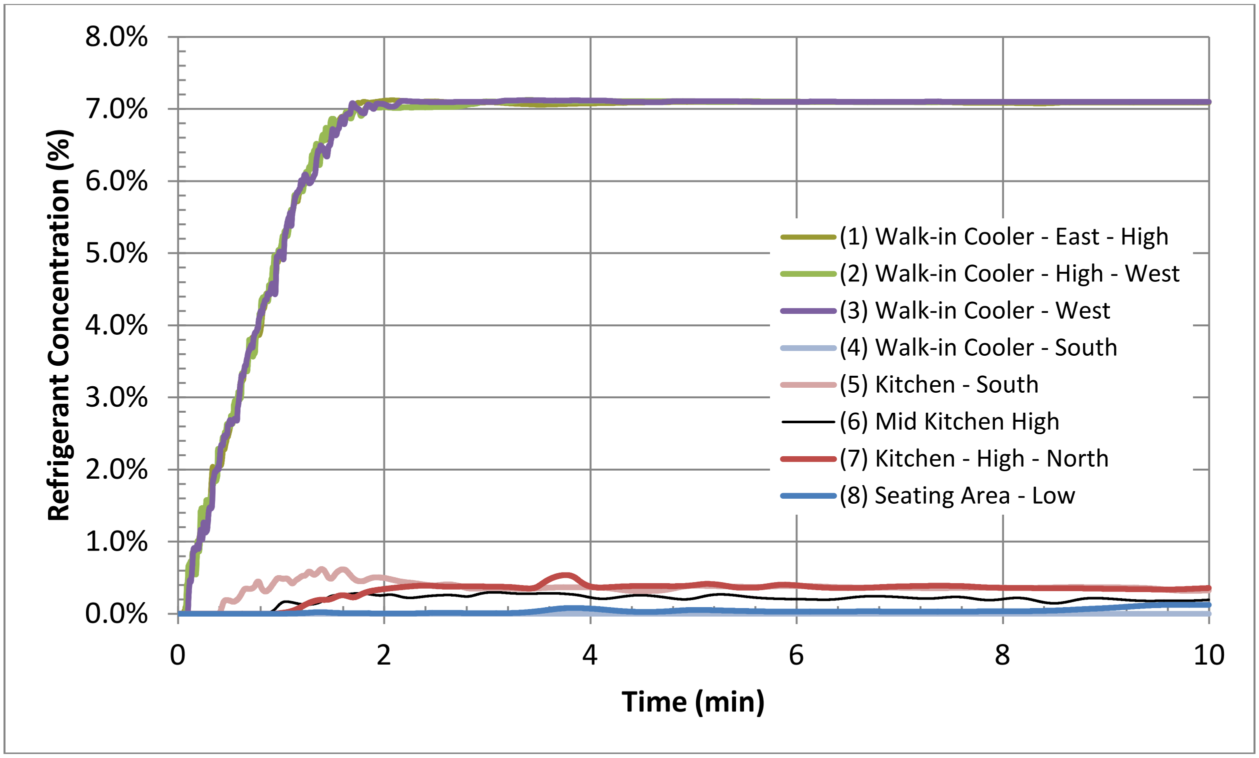


Figure 3.4 CFD-Predicted R-32 Concentrations for the Walk-in Cooler/Restaurant Kitchen Release Scenario (Walk-in Door Closed, 9.5 mm Release)

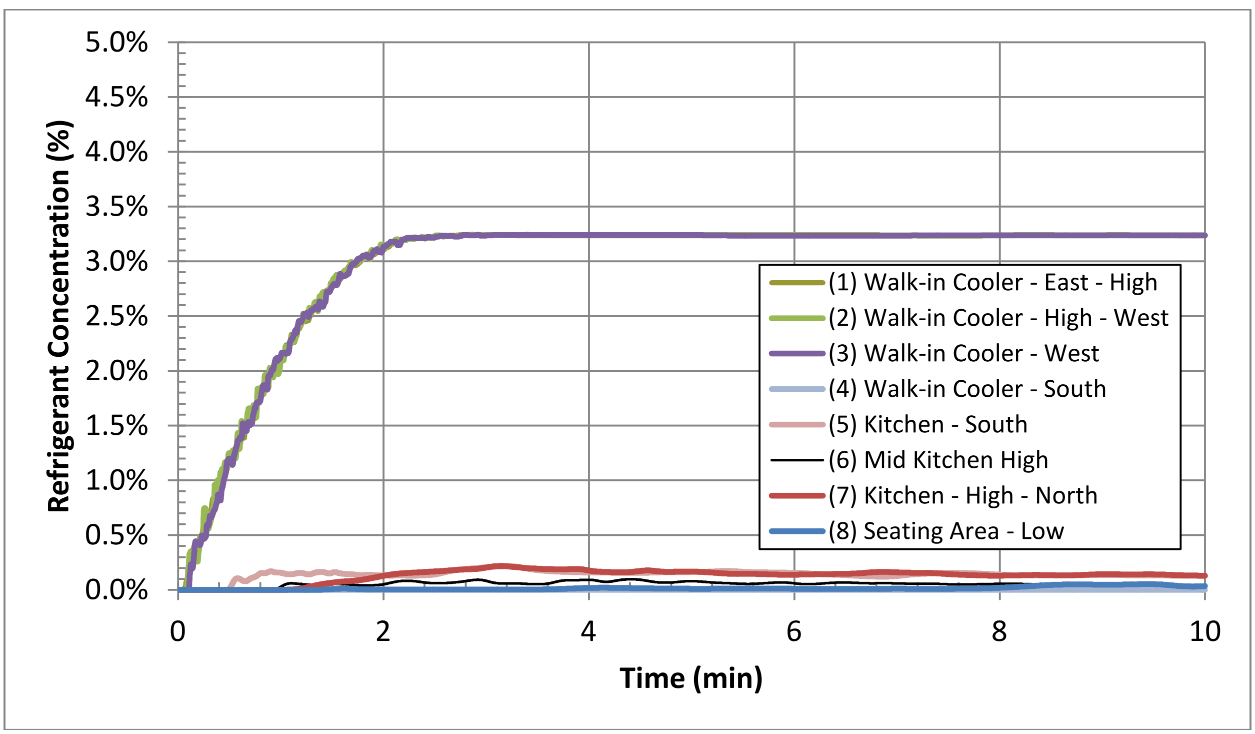


Figure 3.5 CFD-Predicted R-1234ze(E) Concentrations for the Walk-in Cooler/Restaurant Kitchen Release Scenario (Walk-in Door Closed, 9.5 mm Release)

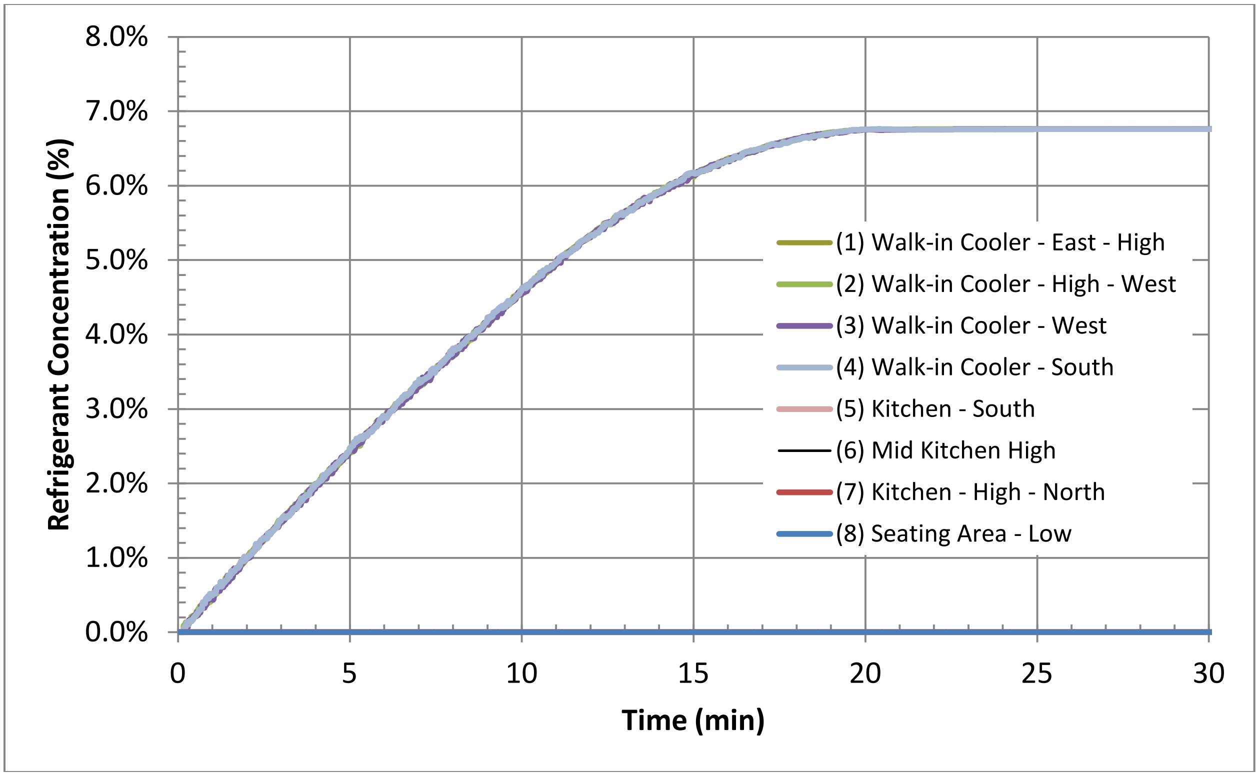


Figure 3.6 CFD-Predicted R-32 Concentrations for the Walk-in Cooler/Restaurant Kitchen Release Scenario (Walk-in Door Closed, 1.6 mm Release)

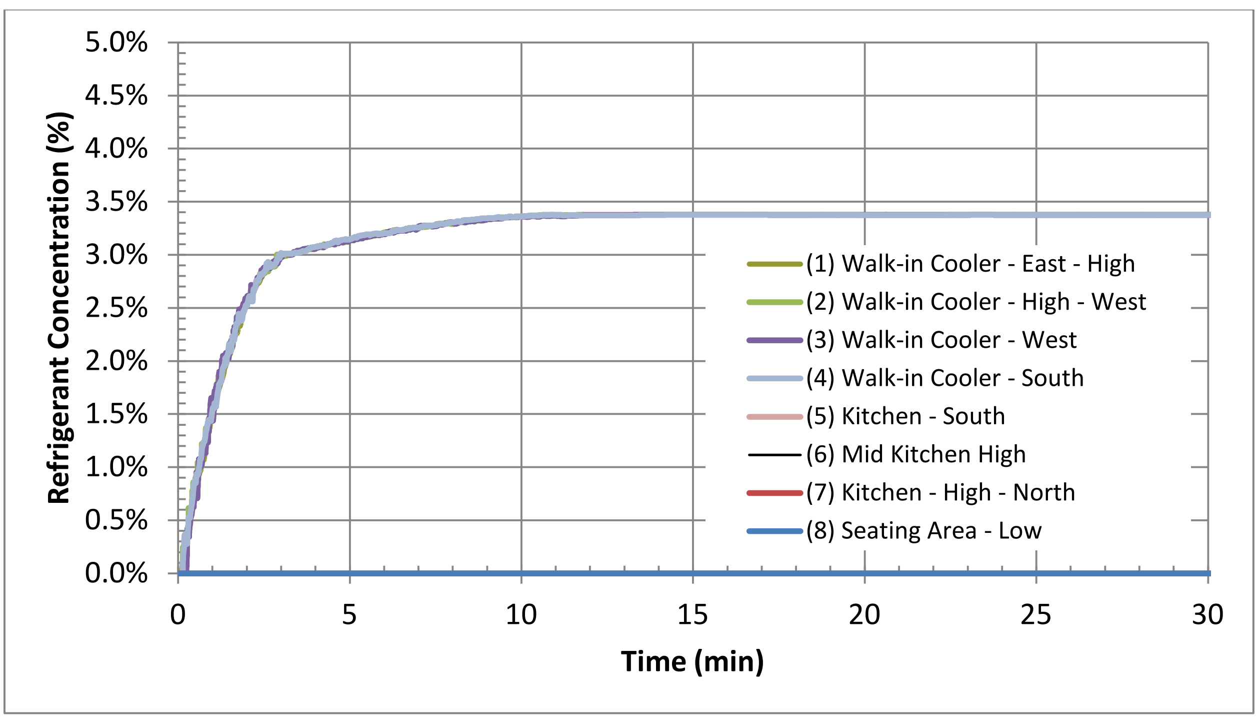


Figure 3.7 CFD-Predicted R-1234ze(E) Concentrations for the Walk-in Cooler/Restaurant Kitchen Release Scenario (Walk-in Door Closed, 1.6 mm Release)

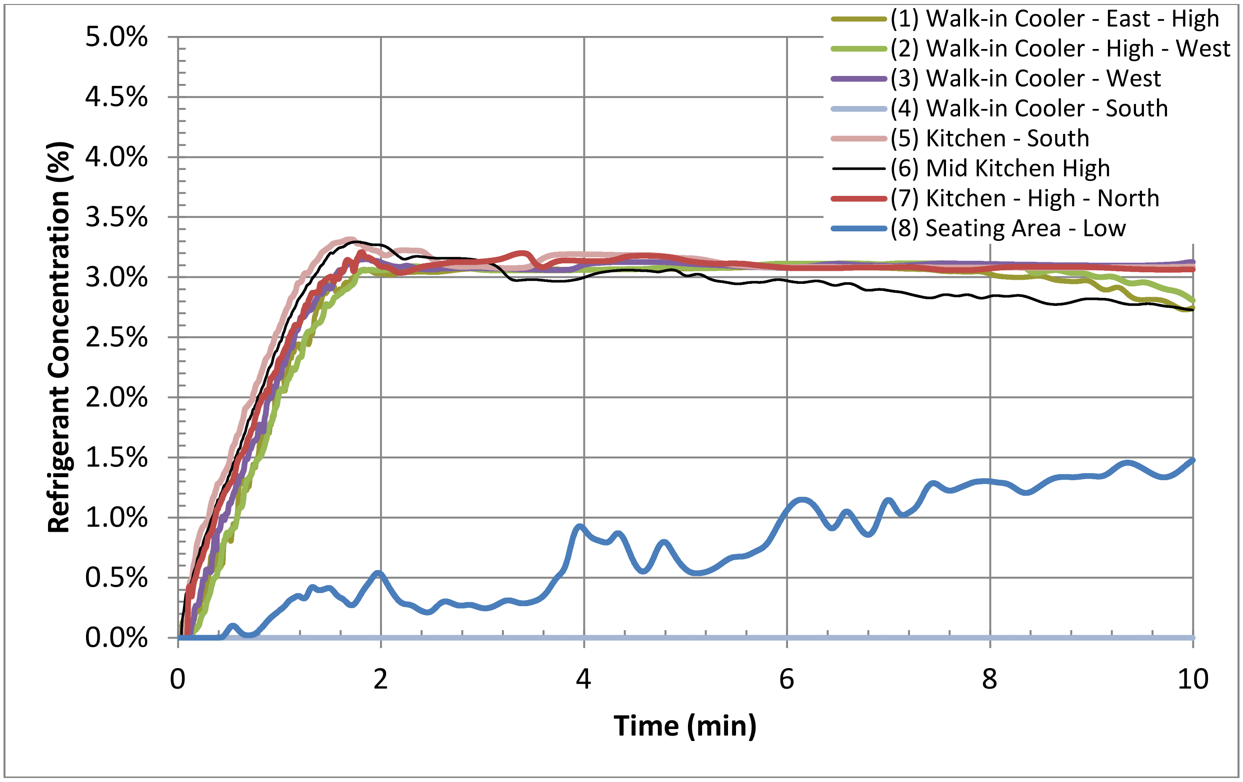


Figure 3.8 CFD-Predicted R-32 Concentrations for the Walk-in Cooler/Restaurant Kitchen Release Scenario (Walk-in Door Open, 9.5 mm Release)

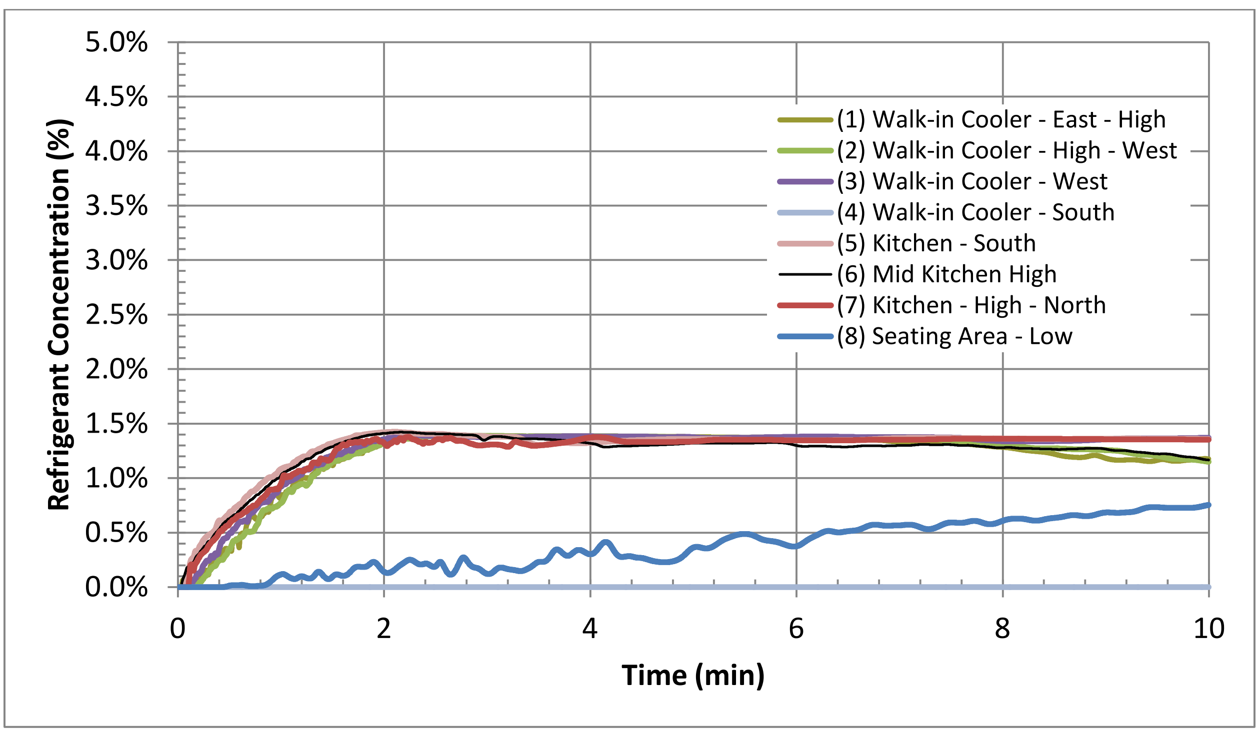


Figure 3.9 CFD-Predicted R-1234ze(E) Concentrations for the Walk-in Cooler/Restaurant Kitchen Release Scenario (Walk-in Door Open, 9.5 mm Release)

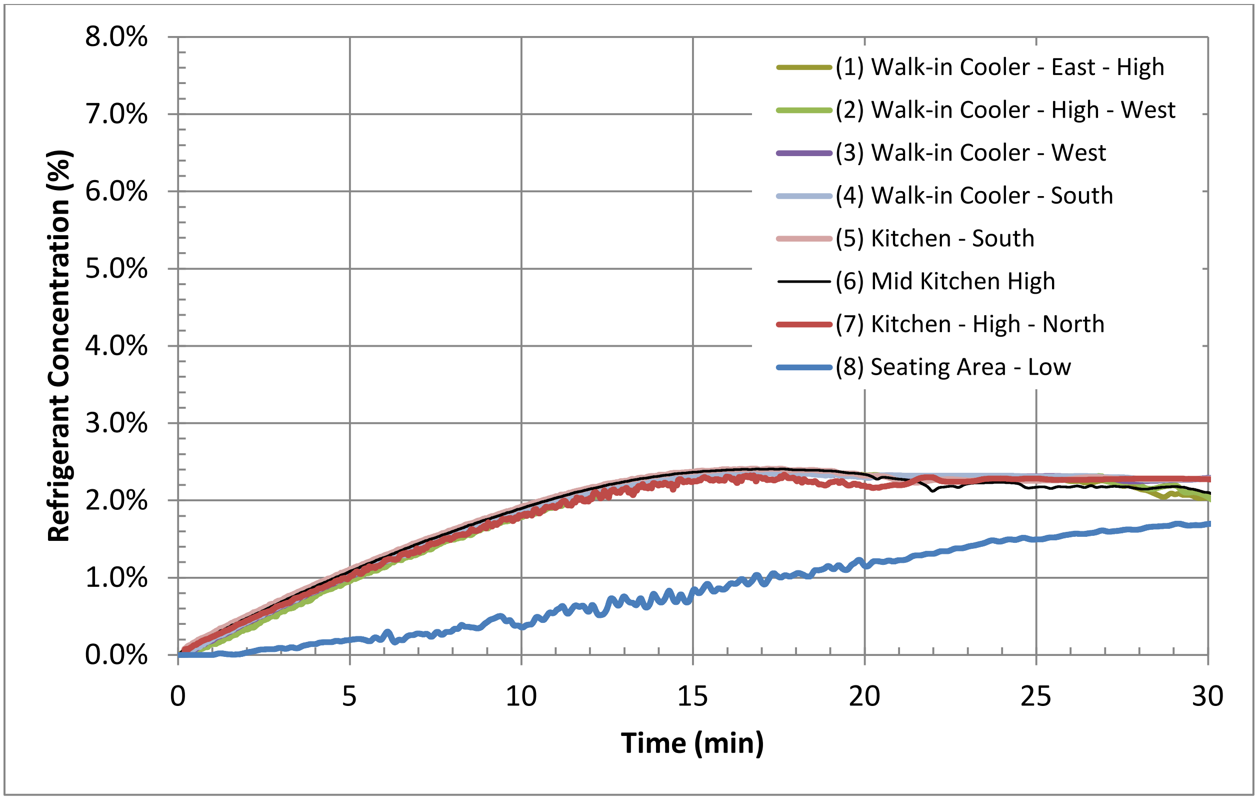


Figure 3.10 CFD-Predicted R-32 Concentrations for the Walk-in Cooler/Restaurant Kitchen Release Scenario (Walk-in Door Open, 1.6 mm Release)

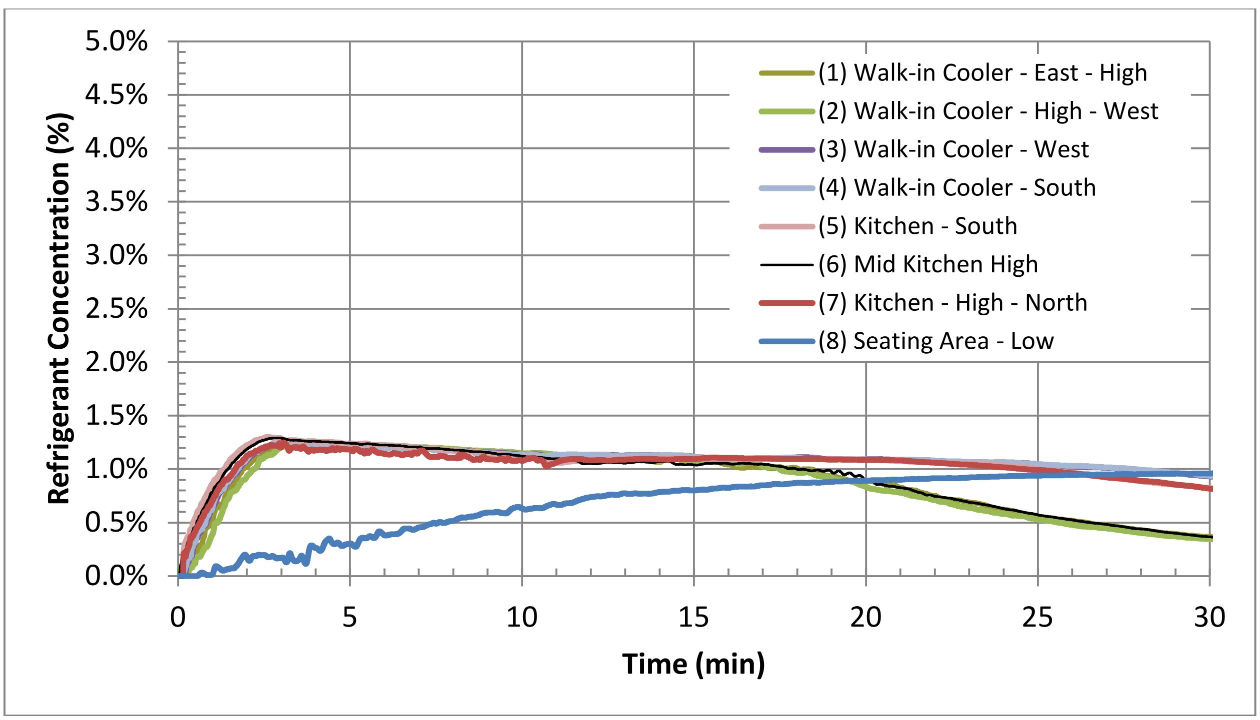


Figure 3.11 CFD-Predicted R-1234ze(E) Concentrations for the Walk-in Cooler/Restaurant Kitchen Release Scenario (Walk-in Door Open, 1.6 mm Release)

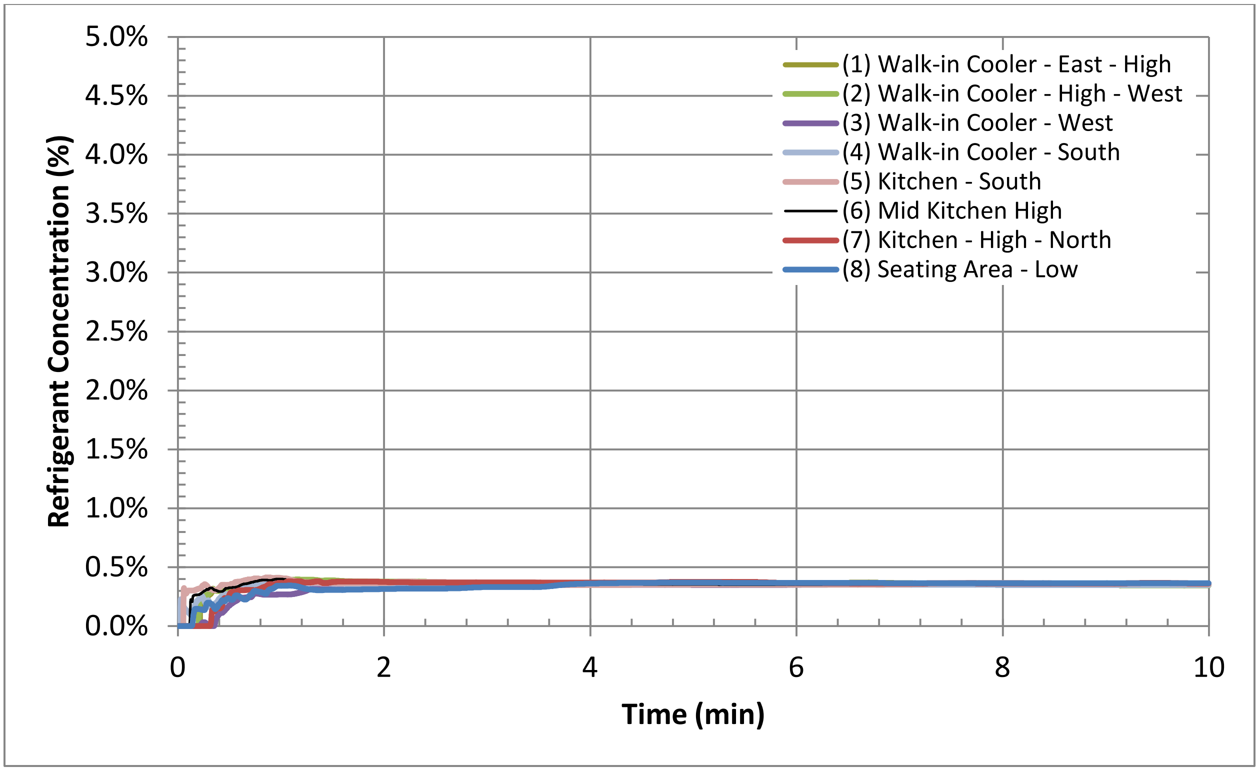


Figure 3.12 CFD-Predicted R-32 Concentrations for the Lunch Counter Release Scenario (9.5 mm Release)

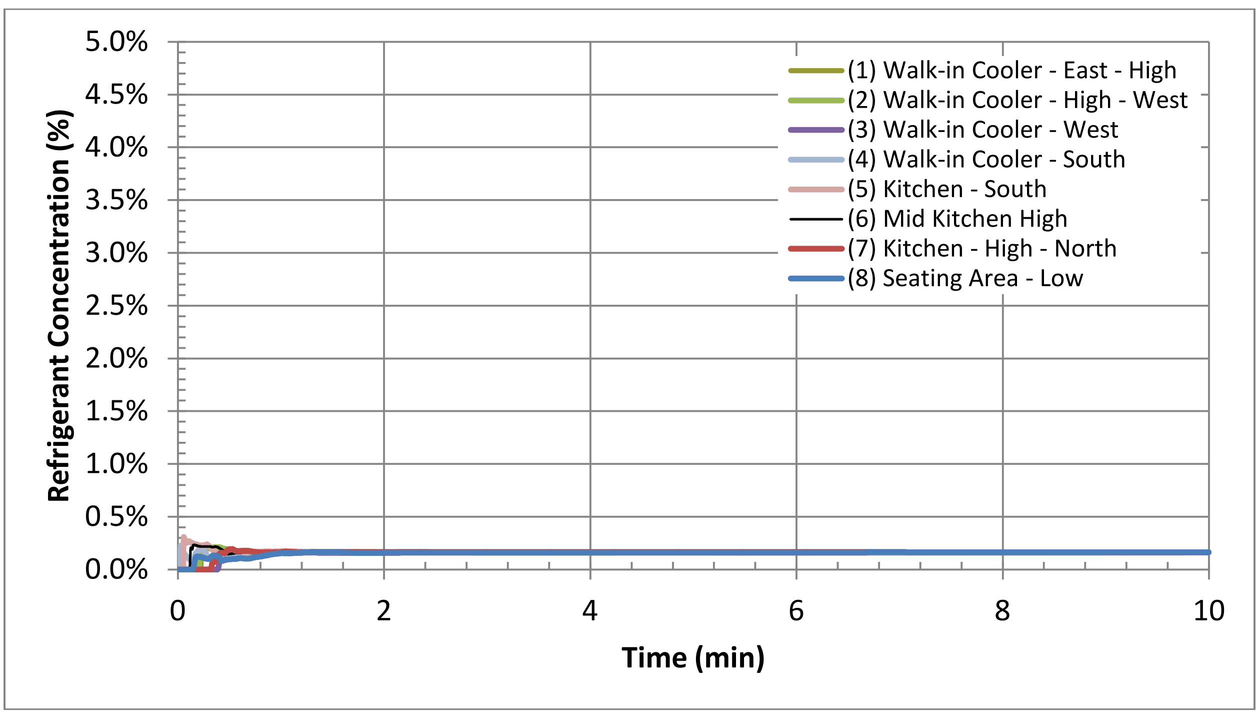


Figure 3.13 CFD-Predicted R-1234ze(E) Concentrations for the Lunch Counter Release Scenario (9.5 mm Release)

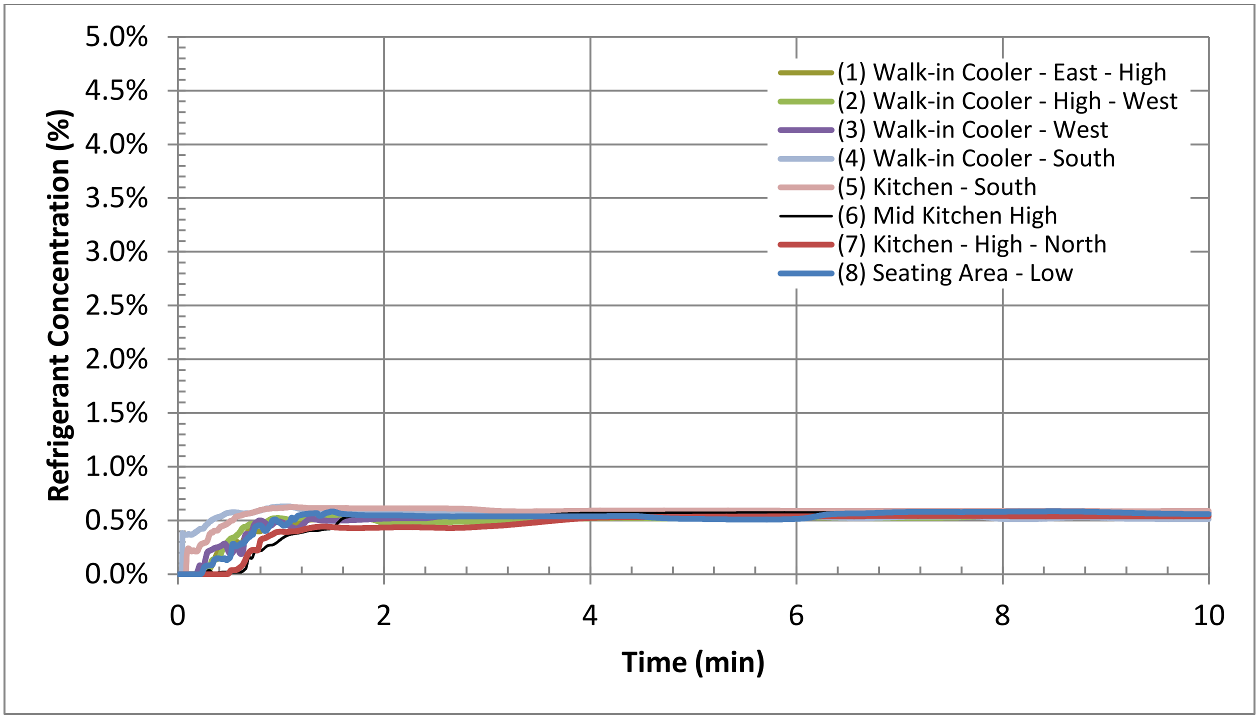


Figure 3.14 CFD-Predicted R-32 Concentrations for the Convenience Store Release Scenario (9.5 mm Release)

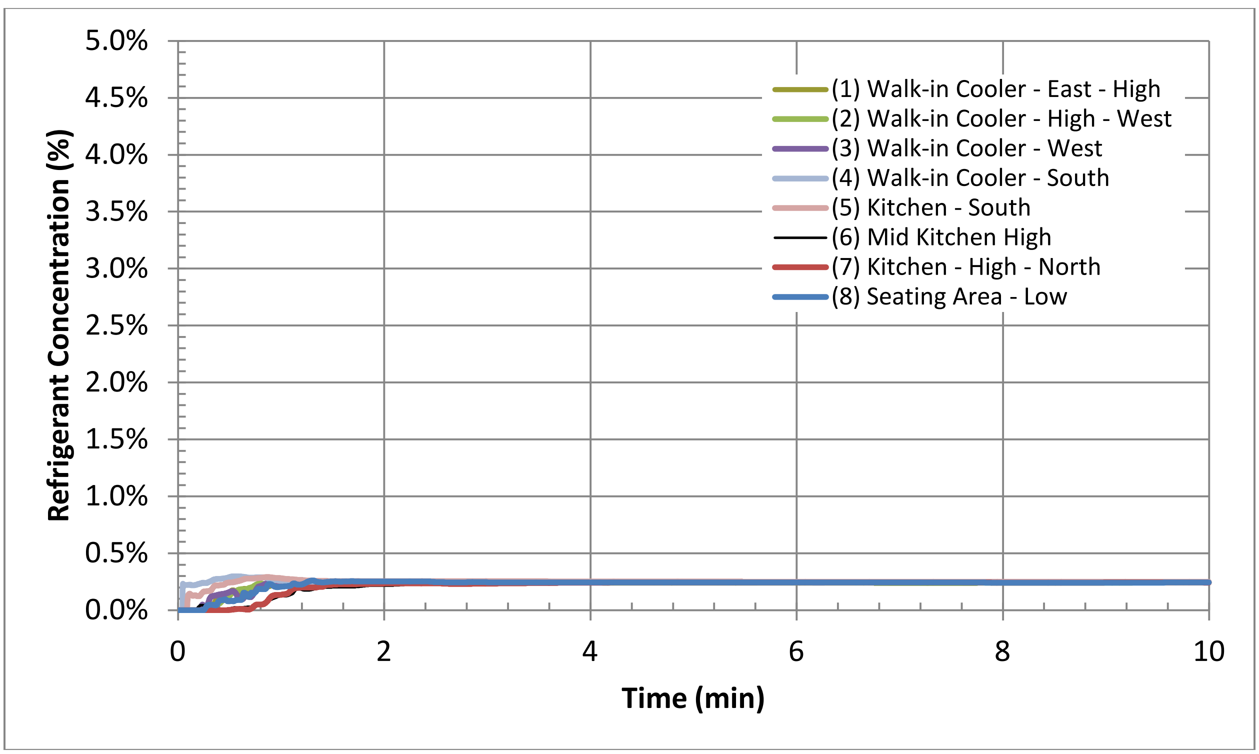


Figure 3.15 CFD-Predicted R-1234ze(E) Concentrations for the Convenience Store Release Scenario (9.5 mm Release)

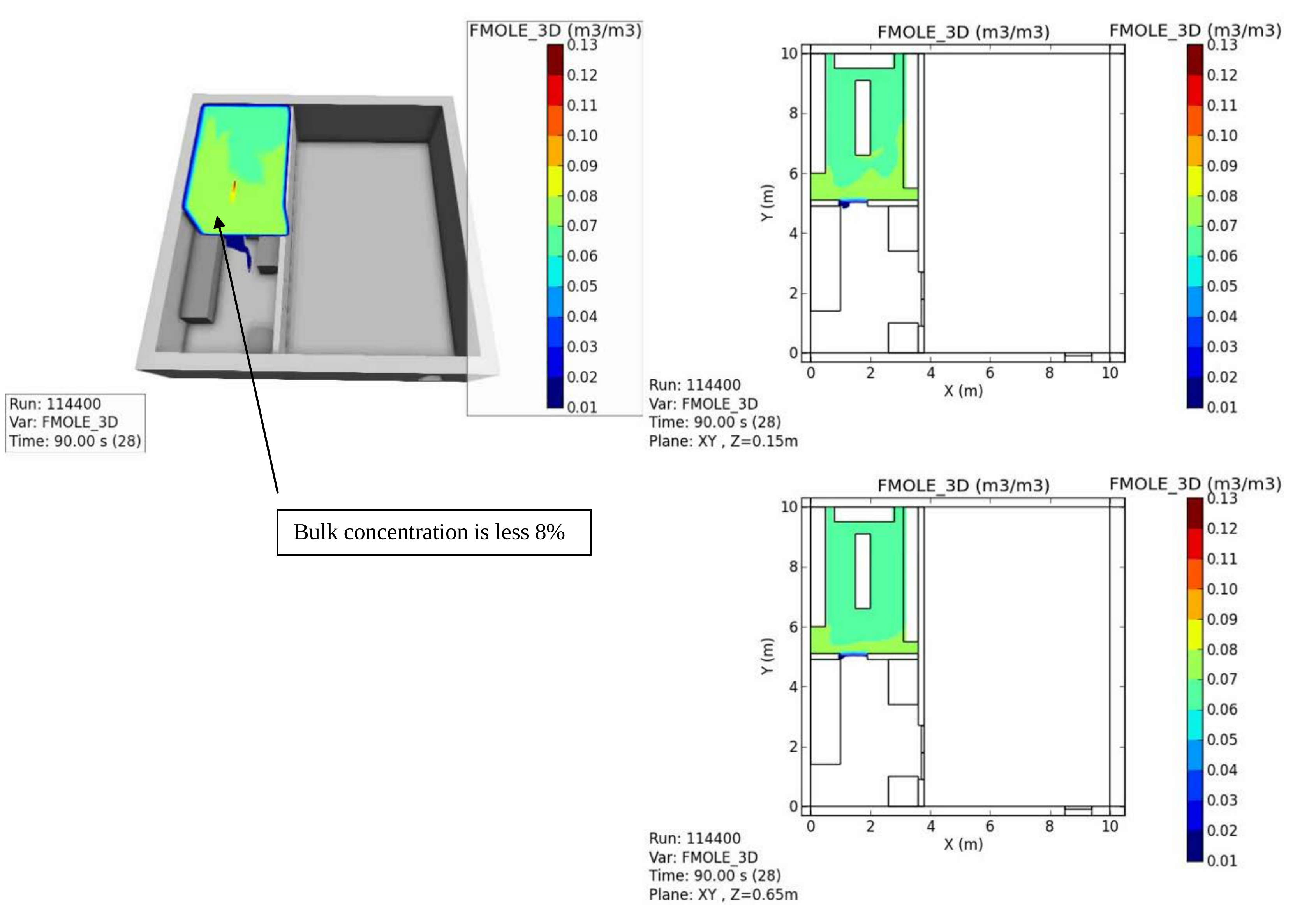


Figure 3.16 Screen capture from CFD simulation videos of an R-32 release in the Walk-in Cooler/Restaurant Kitchen Release Scenario (Walk-in Door Closed, 9.5 mm Release) at near-maximum concentrations.

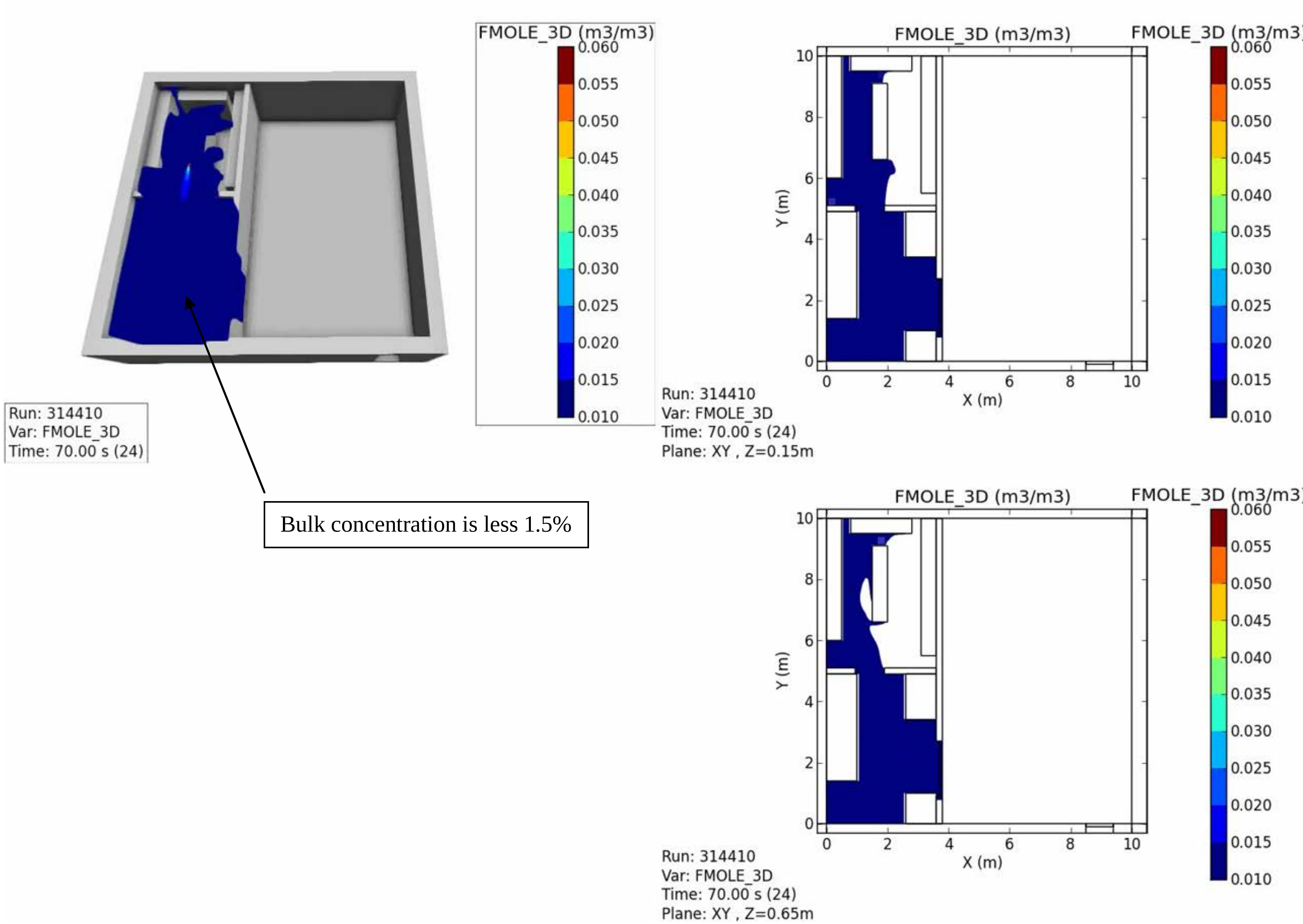


Figure 3.17 Screen capture from CFD simulation videos of an R-1234ze(E) release in the Walk-in Cooler/Restaurant Kitchen Scenario (Walk-in Door Open, 9.5 mm Release).

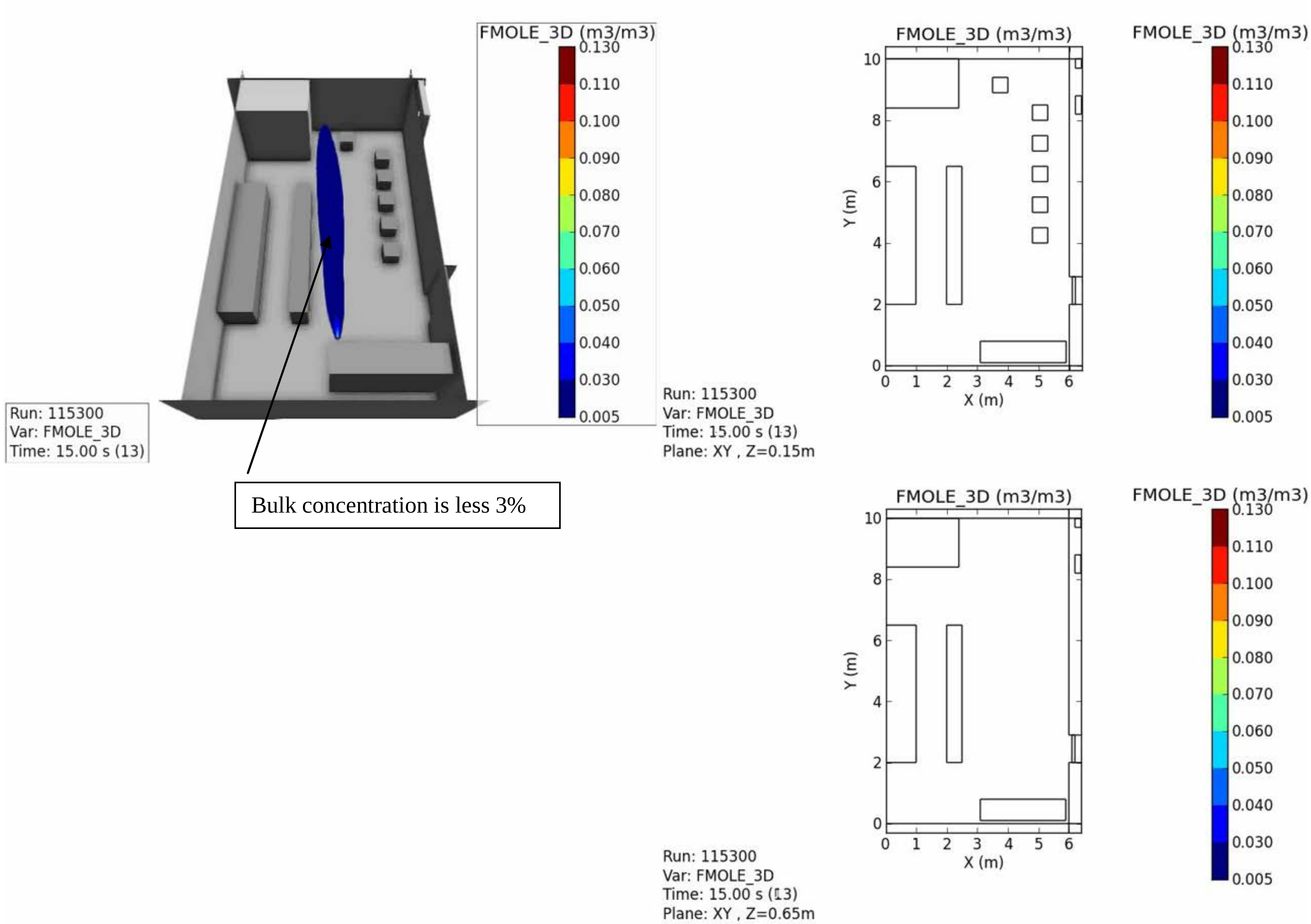


Figure 3.18 Screen capture from CFD simulation videos of an R-32 release in the Lunch Counter Scenario (9.5 mm Release).

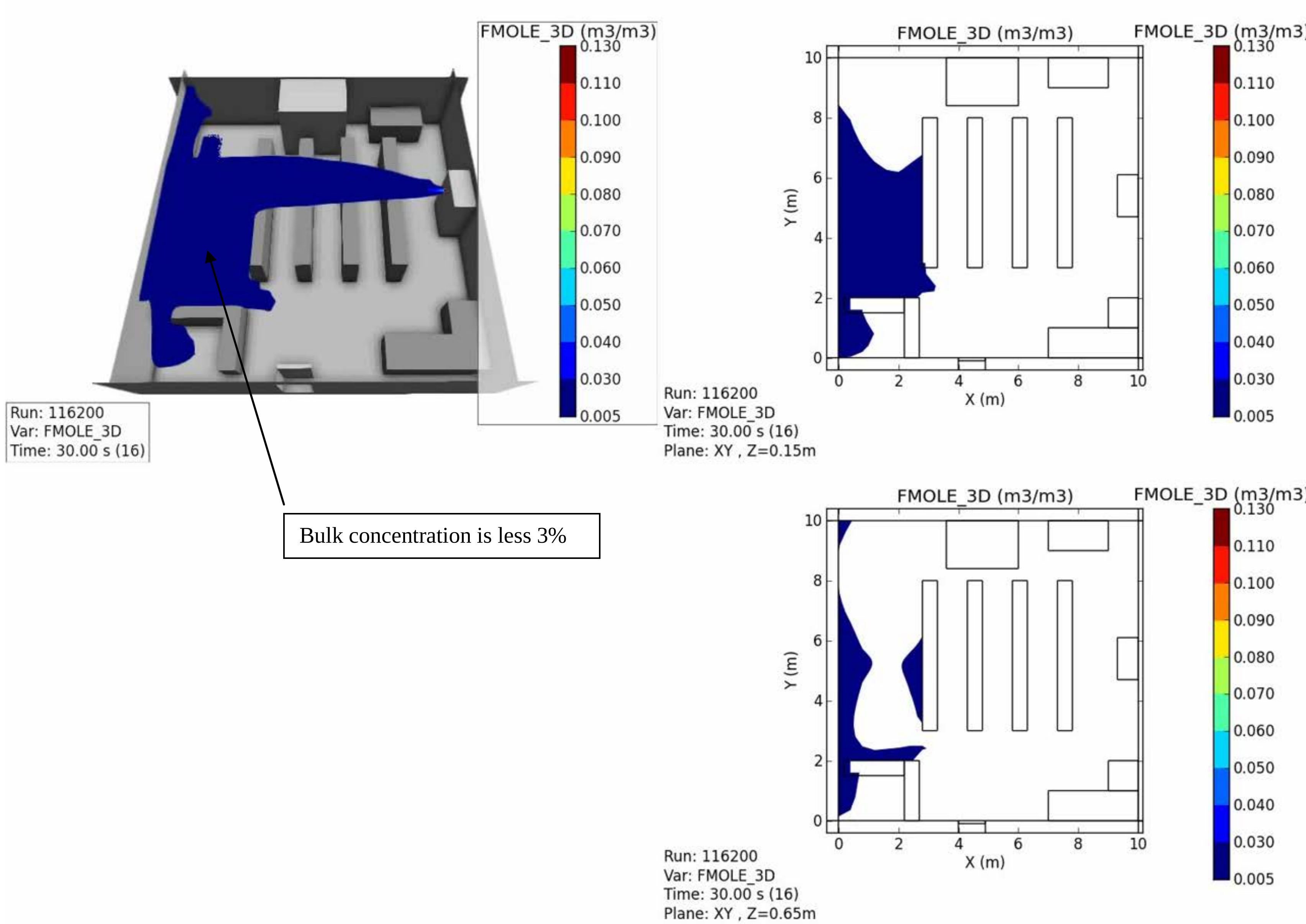


Figure 3.19 Screen capture from CFD simulation videos of an R-32 release in the Convenience Store Scenario (9.5 mm Release).

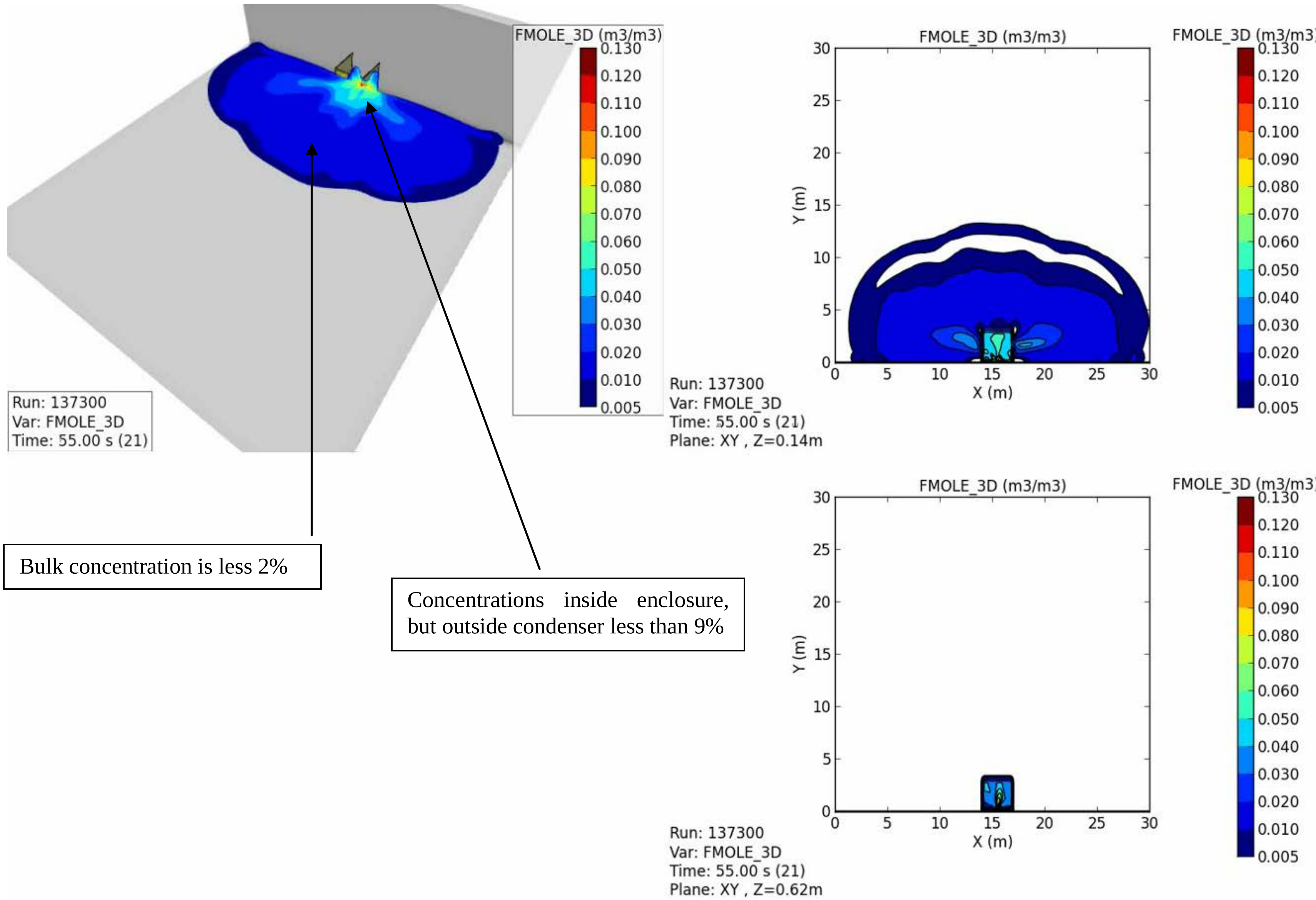


Figure 3.20 Screen capture from CFD simulation videos of an R-32 release in the outdoor condenser with a 10 ft. by 10 ft. surrounding enclosure.

Figure 3.21 Example of Obstructions Simulated with Cardboard Boxes (Restaurant Scenario, Walk-in Interior)

Figure 3.22 Example of Obstructions Simulated with Cardboard Boxes (Convenience Store Scenario)

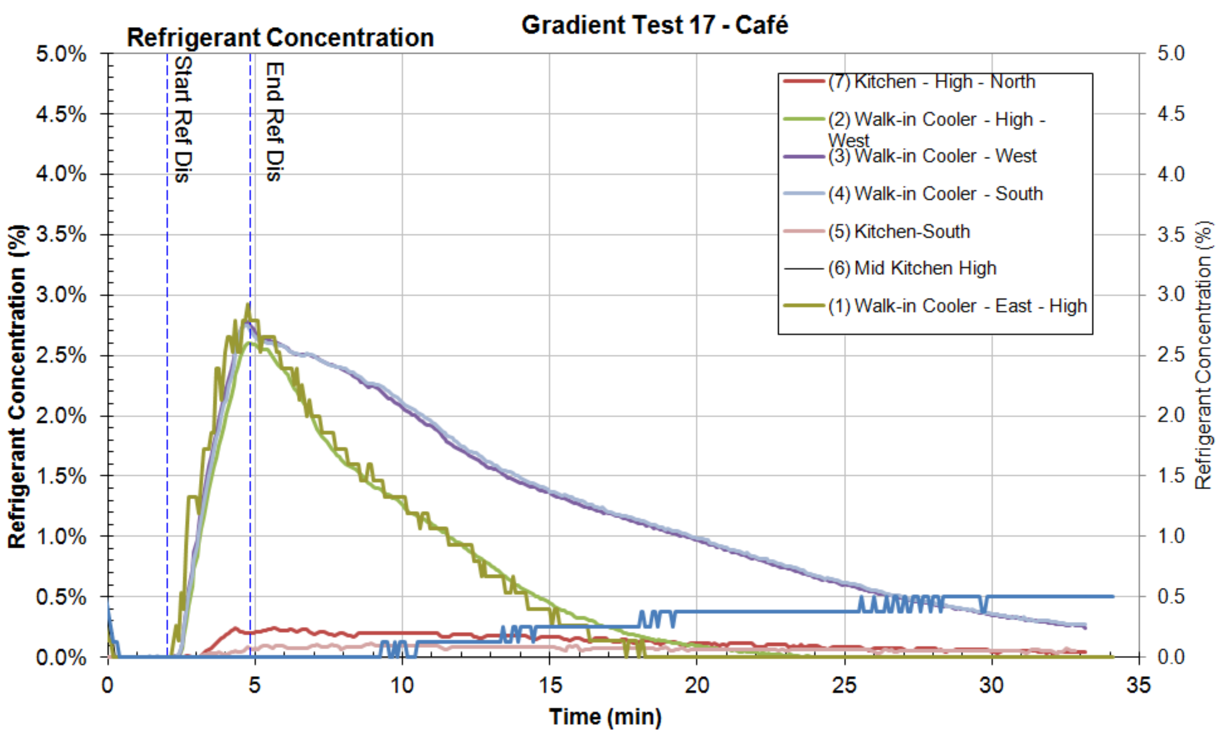


Figure 3.23 Experimental R-1234ze(E) Concentrations for Walk-in/Restaurant Kitchen Release Scenario (Walk-in Cooler Door Closed, 9.5 mm Release)

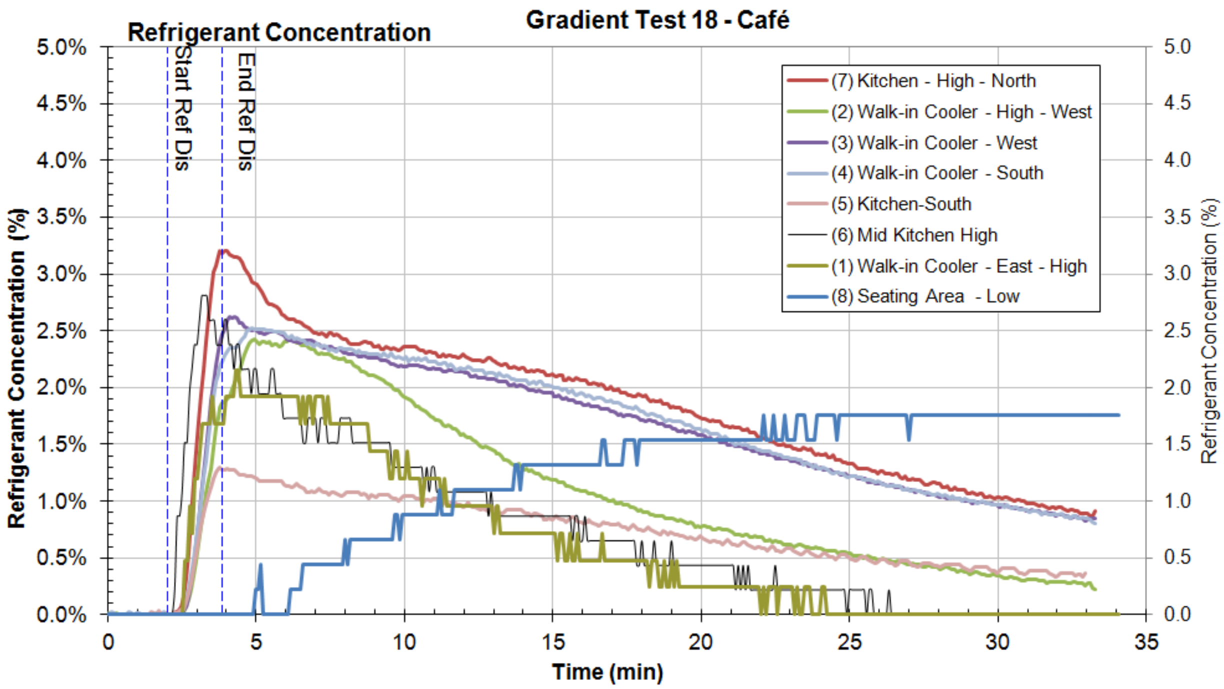


Figure 3.24 Experimental R-32 Concentrations for Walk-in/Restaurant Kitchen Release Scenario (Walk-in Cooler Door Open, 9.5 mm Release)

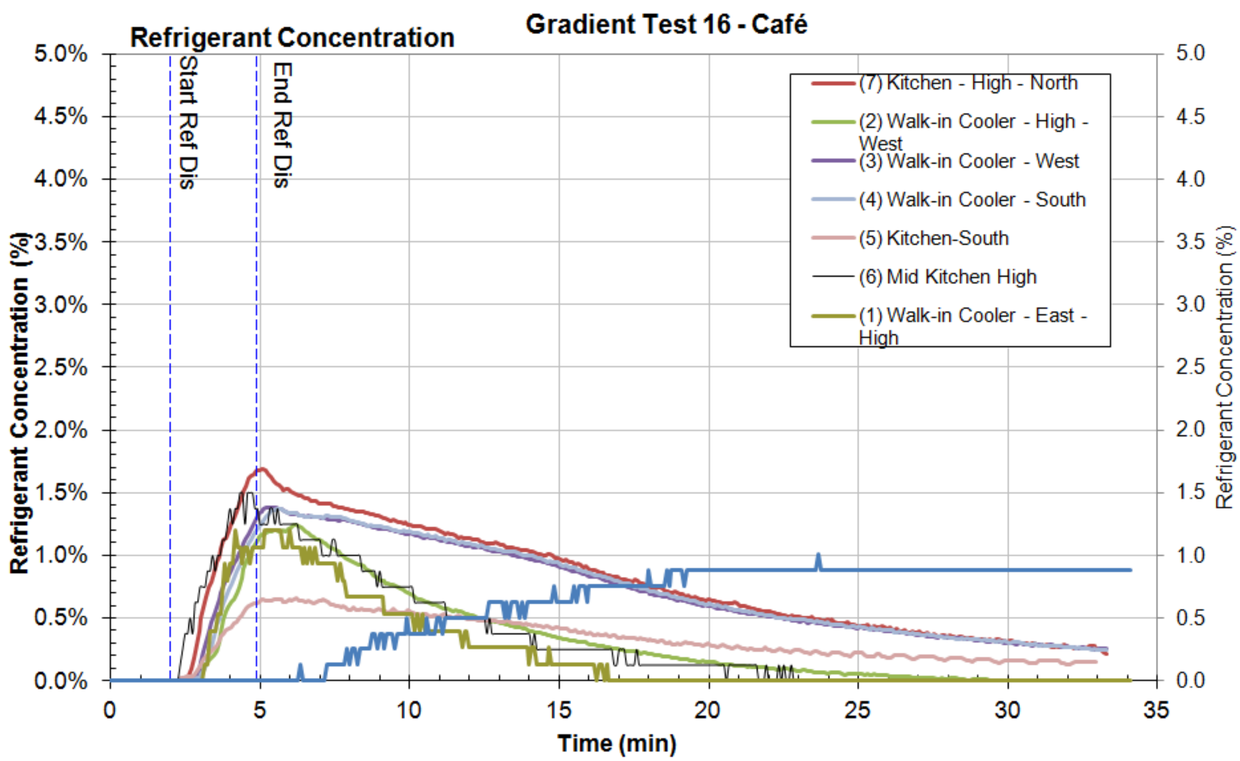


Figure 3.25 Experimental R-1234ze(E) Concentrations for Walk-in/Restaurant Kitchen Release Scenario (Walk-in Cooler Door Open, 9.5 mm Release)

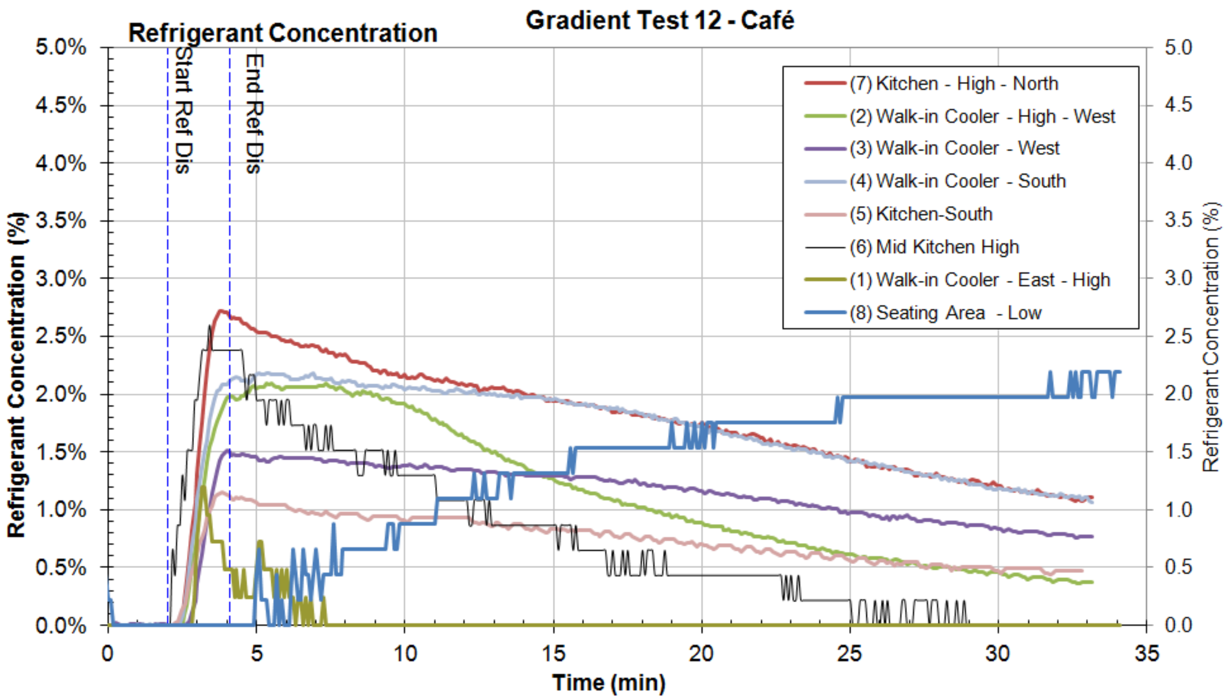


Figure 3.26 Experimental R-32 Concentrations for Walk-in/Restaurant Kitchen Release Scenario (Walk-in Cooler Door Open, 3.2 mm Release)

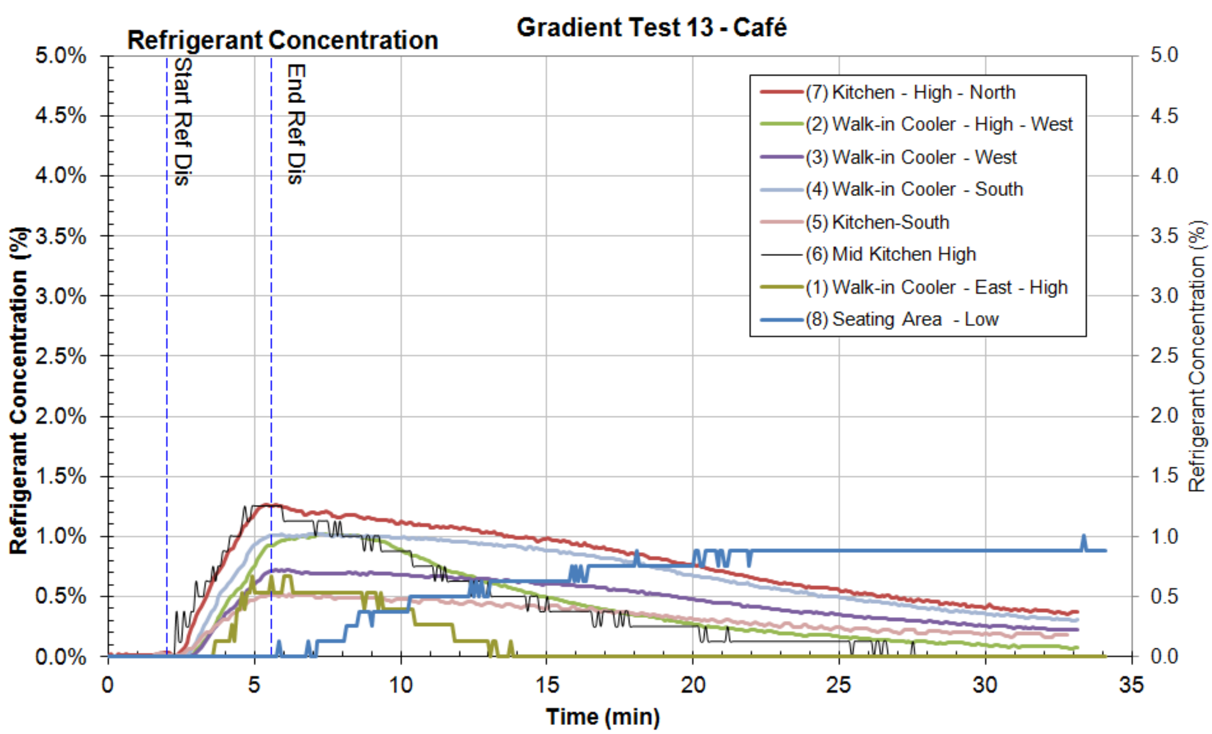


Figure 3.27 Experimental R-1234ze(E) Concentrations for Walk-in/Restaurant Kitchen Release Scenario (Walk-in Cooler Door Open, 3.2 mm Release)

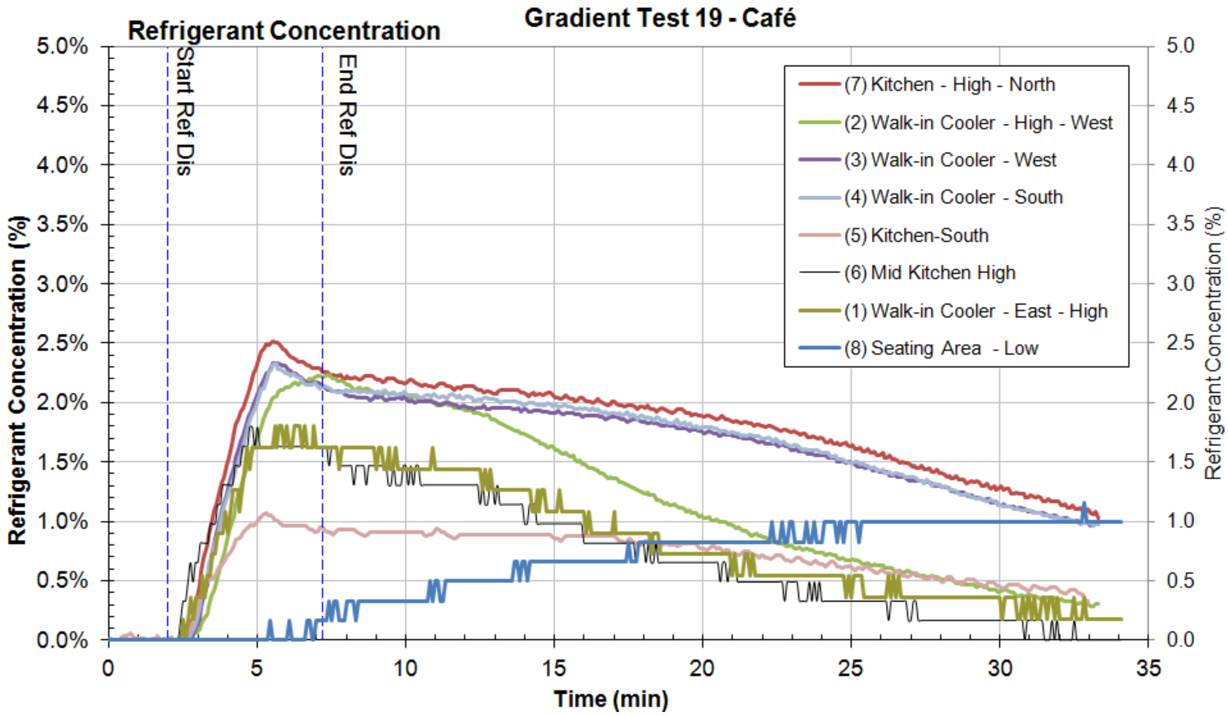


Figure 3.28 Experimental R-32 Concentrations for Walk-in/Restaurant Kitchen Release Scenario (Walk-in Cooler Door Open, 1.6 mm Release)

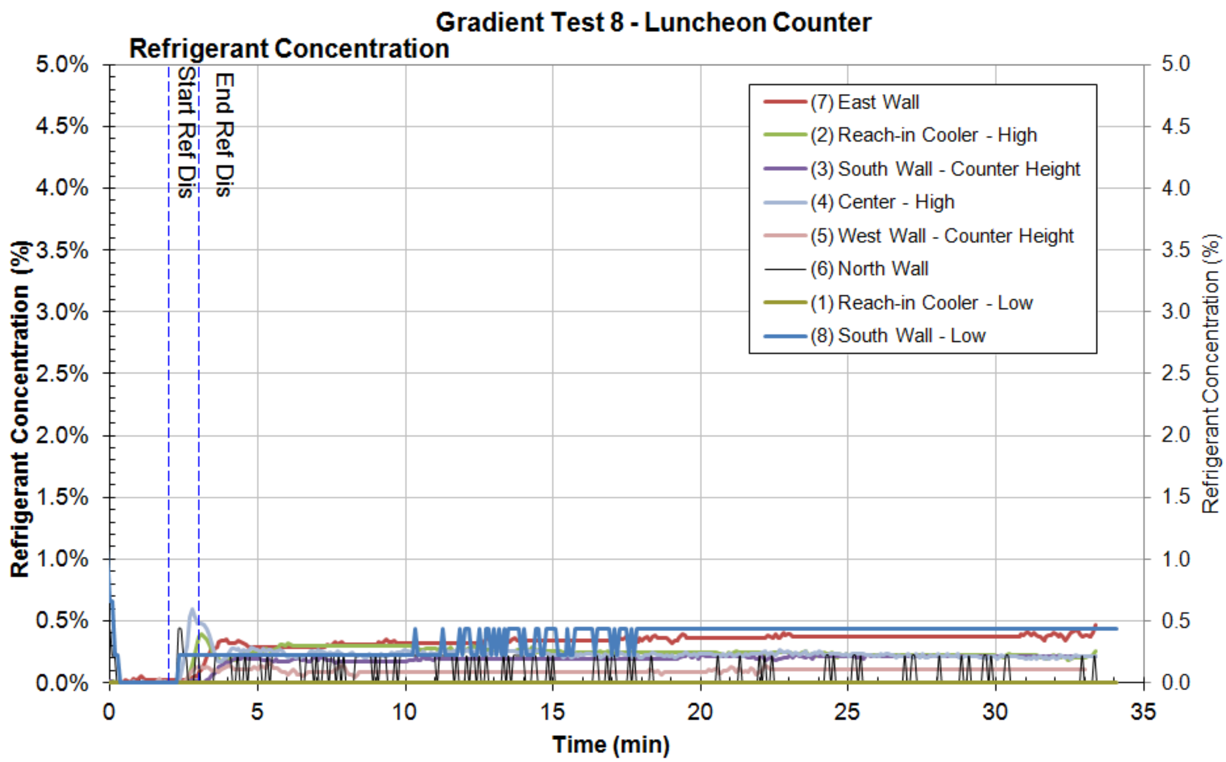


Figure 3.29 Experimental R-32 Concentrations for Lunch Counter Release Scenario (9.5 mm Release)

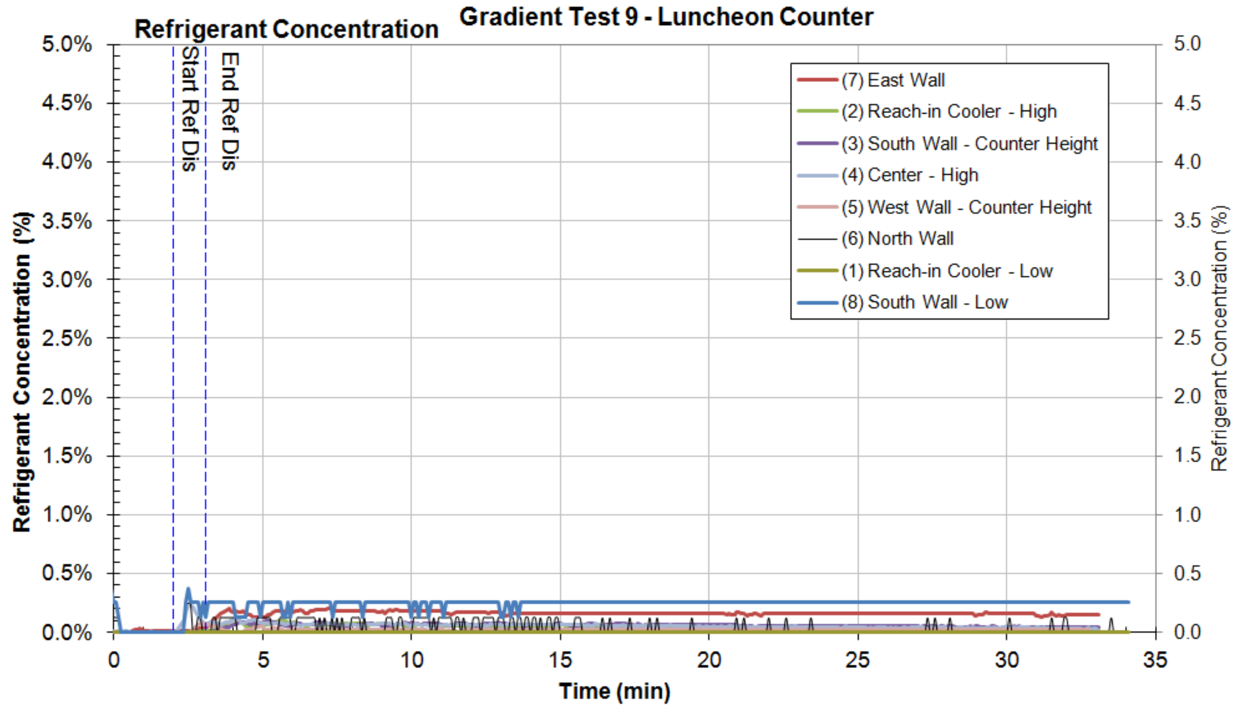


Figure 3.30 Experimental R-1234ze(E) Concentrations for Lunch Counter Release Scenario (9.5 mm Release)

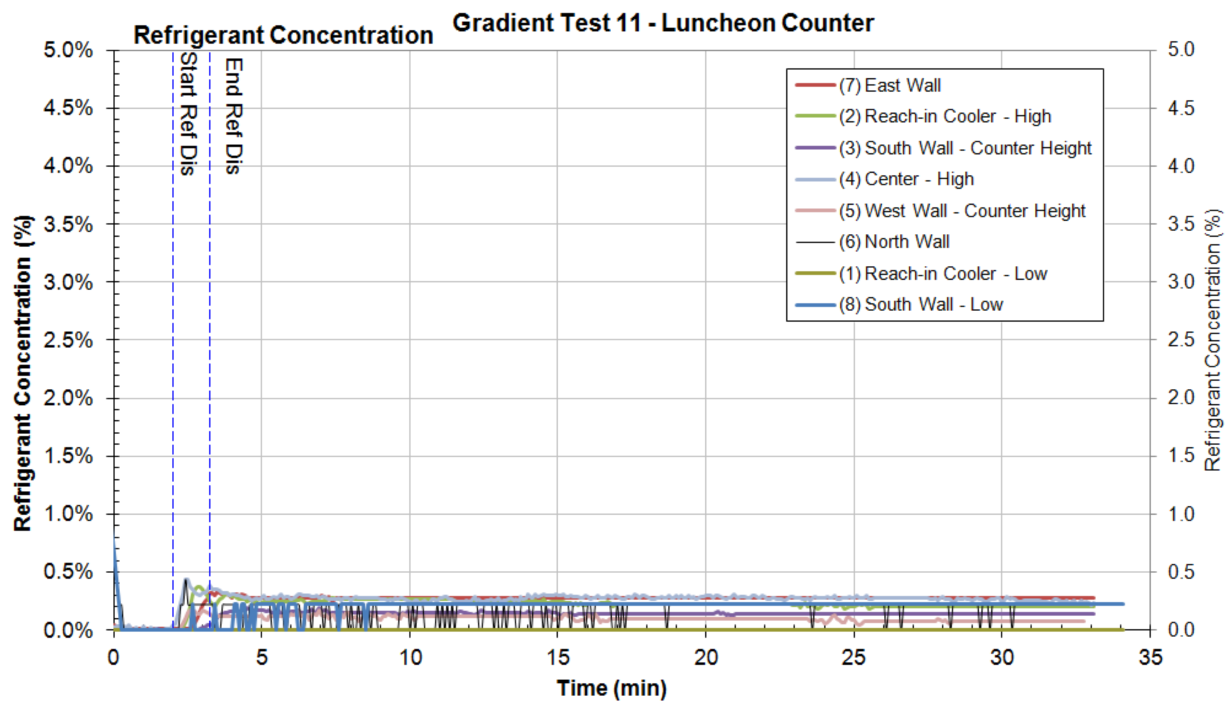


Figure 3.31 Experimental R-32 Concentrations for Lunch Counter Release Scenario (3.2 mm Release)

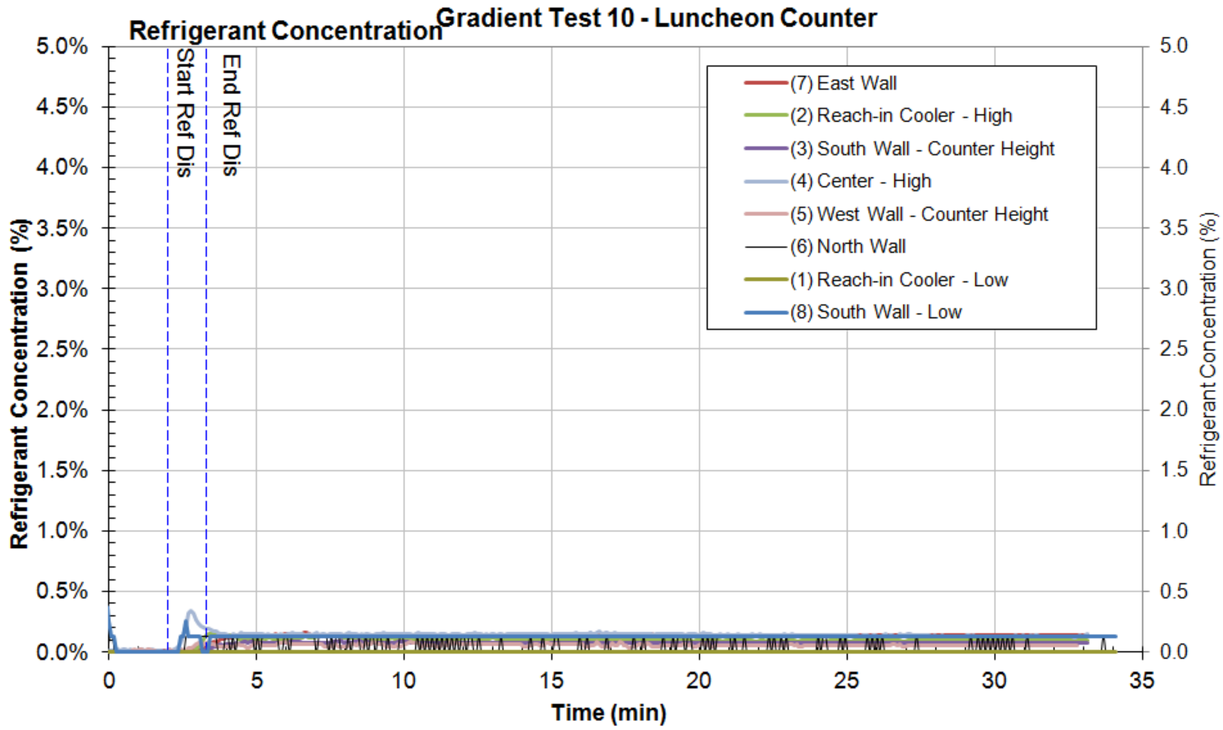


Figure 3.32 Experimental R-1234ze(E) Concentrations for Lunch Counter Release Scenario (3.2 mm Release)

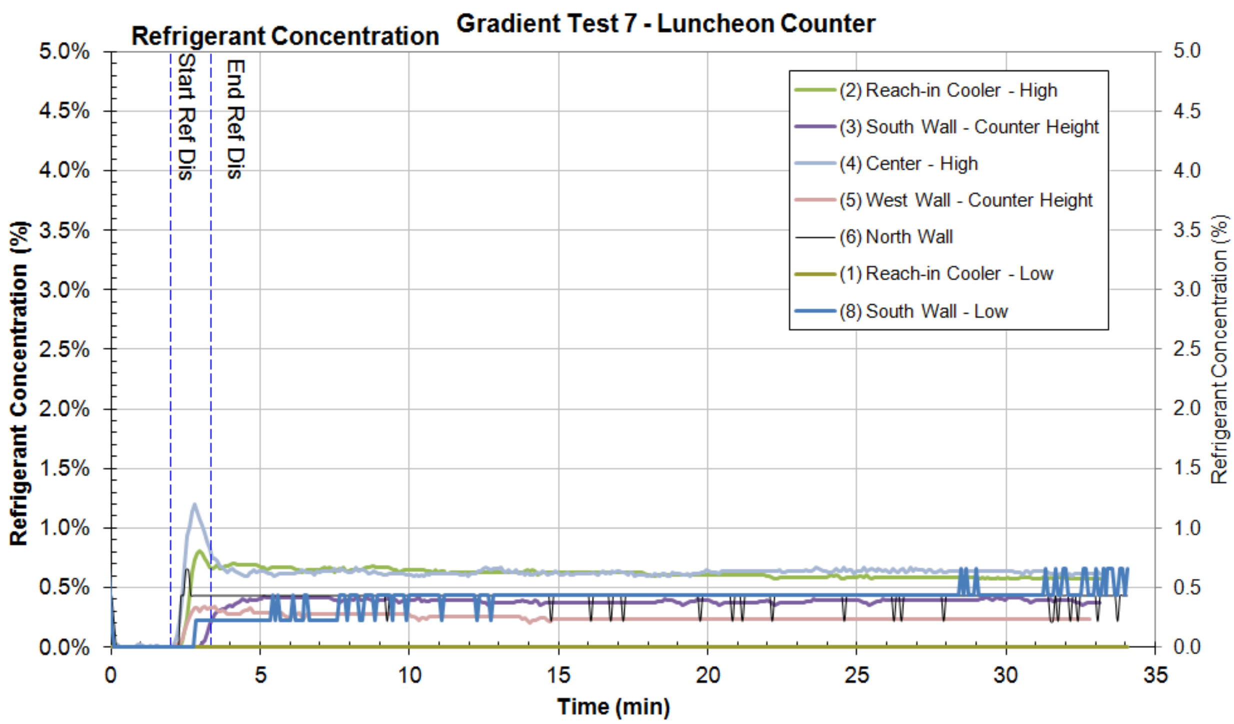


Figure 3.33 Experimental R-32 Concentrations for Lunch Counter Release Scenario (2.3 kg Charge)

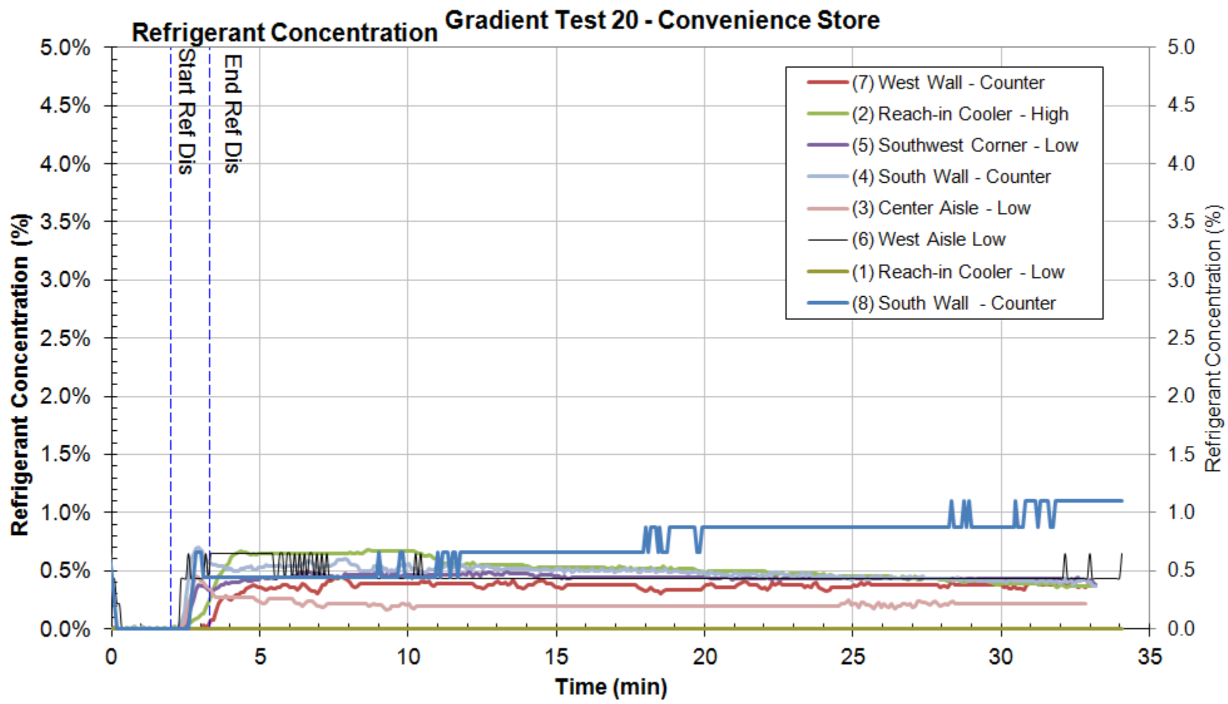


Figure 3.34 Experimental R-32 Concentrations for Convenience Store Release Scenario

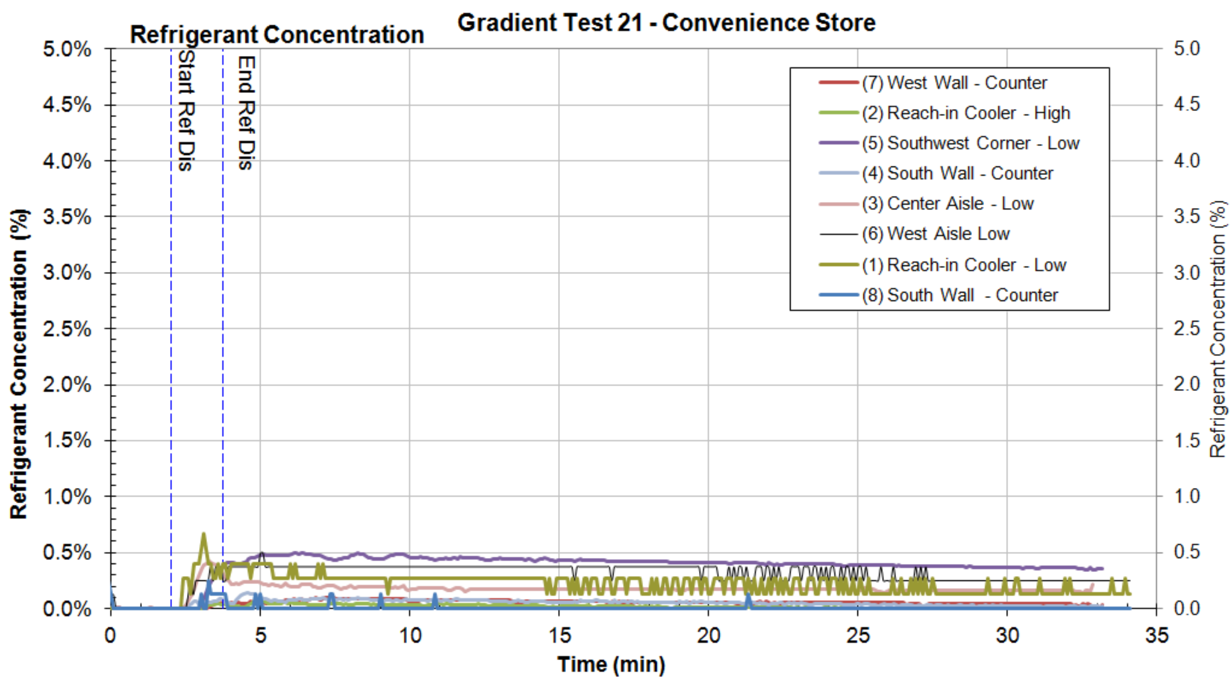
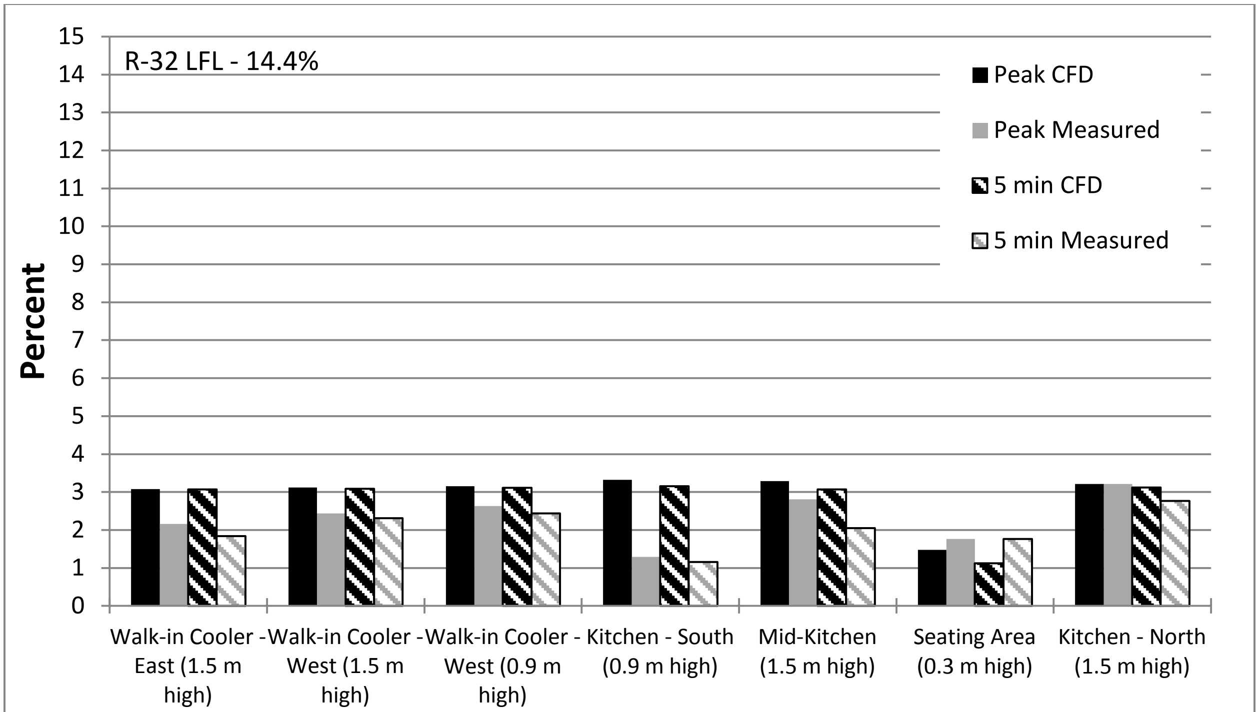
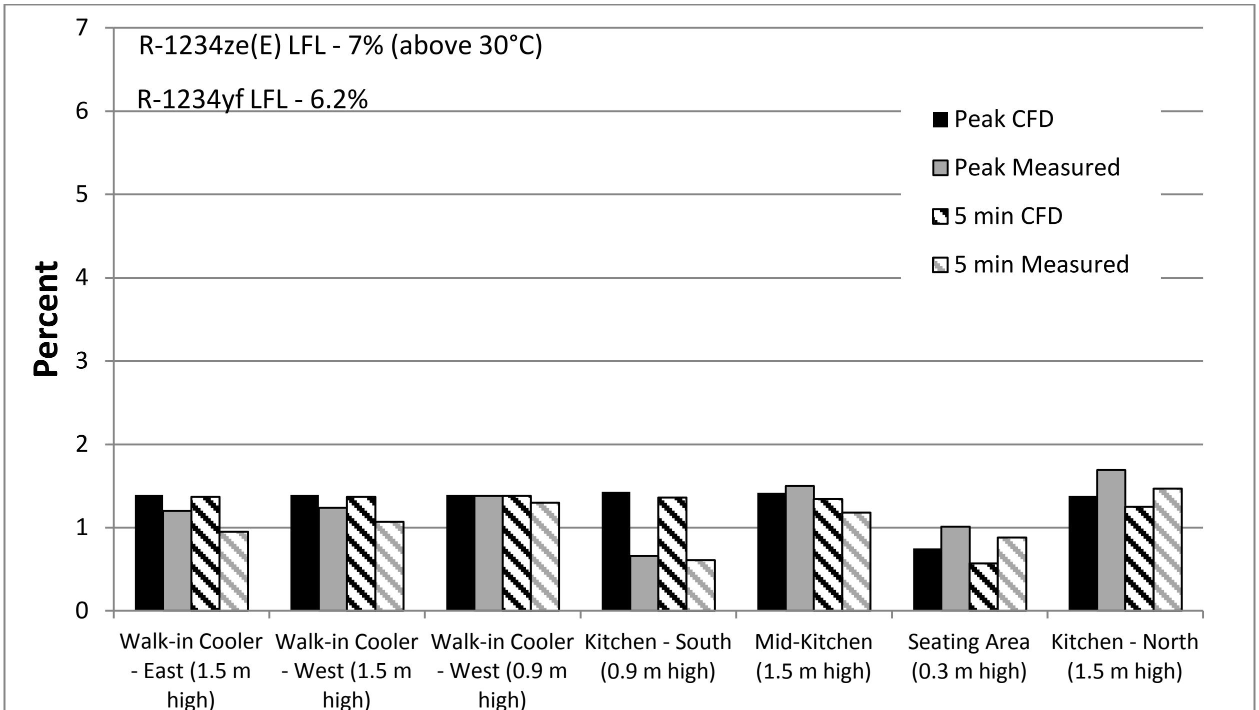


Figure 3.35 Experimental R-1234ze(E) Concentrations for Convenience Store Release Scenario



Data for the Walk-in Cooler - South measurement point not shown due to lack of CFD results at this location.

Figure 3.36 Comparison of CFD Modeling and Experimental Testing Results, R-32, Restaurant/Café Walk-in Cooler Scenario



Data for the Walk-in Cooler - South measurement point not shown due to lack of CFD results at this location.

Figure 3.37 Comparison of CFD Modeling and Experimental Testing Results, R-1234ze(E), Restaurant/Café Walk-in Cooler Scenario

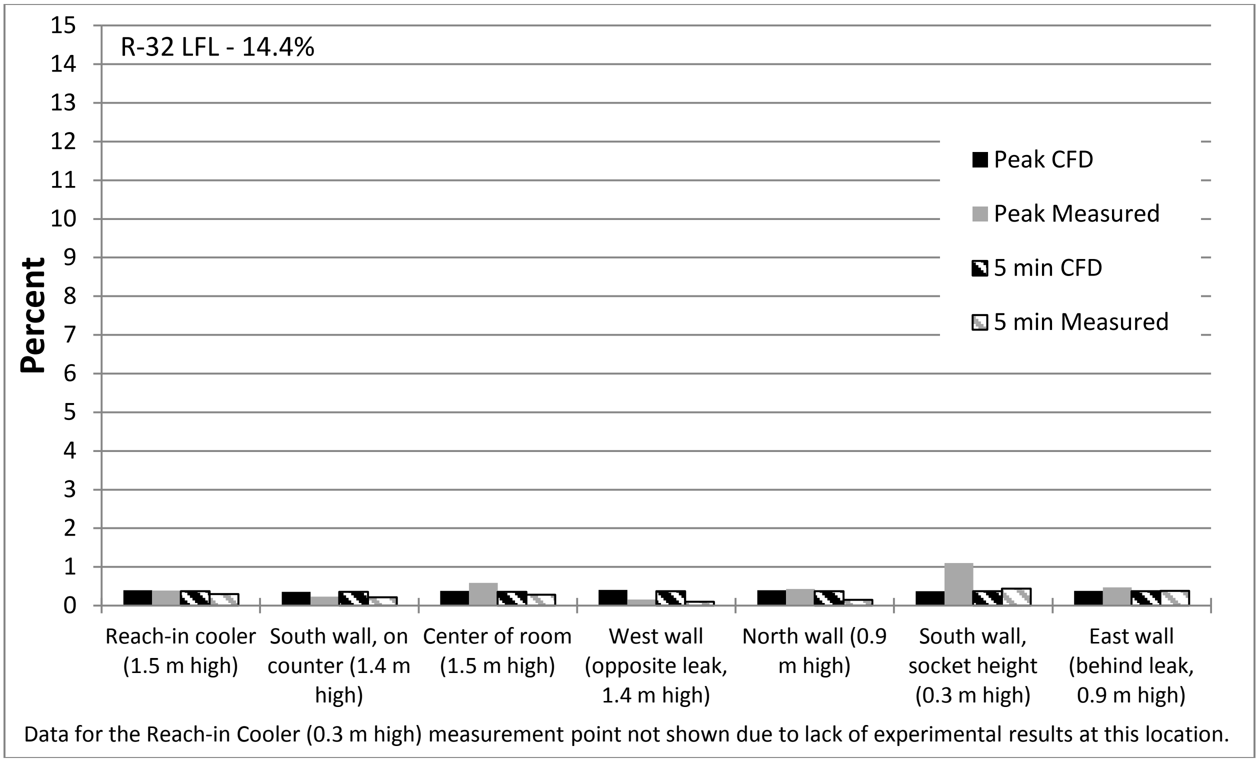


Figure 3.38 Comparison of CFD Modeling and Experimental Testing Results, R-32, Lunch Counter Scenario

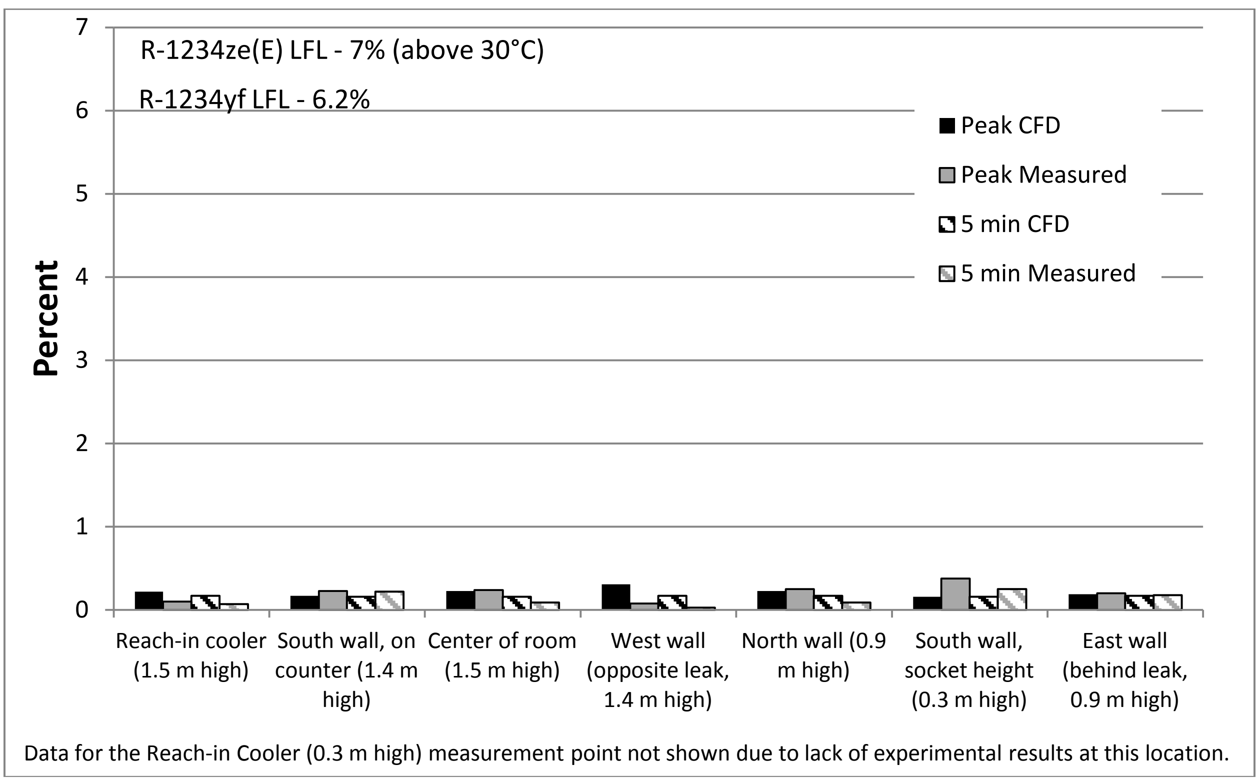
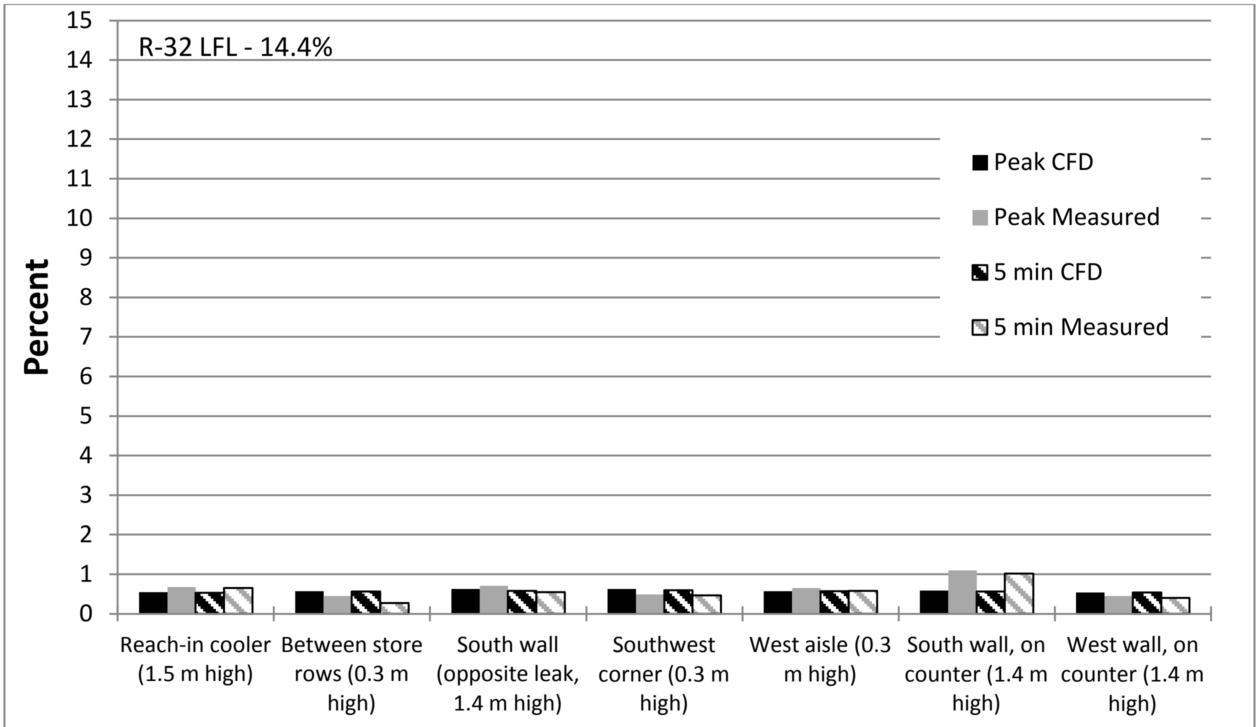


Figure 3.39 Comparison of CFD Modeling and Experimental Testing Results, R-1234ze(E), Lunch Counter Scenario



Data for the Reach-in Cooler (0.3 m high) measurement point not shown due to lack of experimental results at this location.

Figure 3.40 Comparison of CFD Modeling and Experimental Testing Results, R-32, Convenience Store Scenario

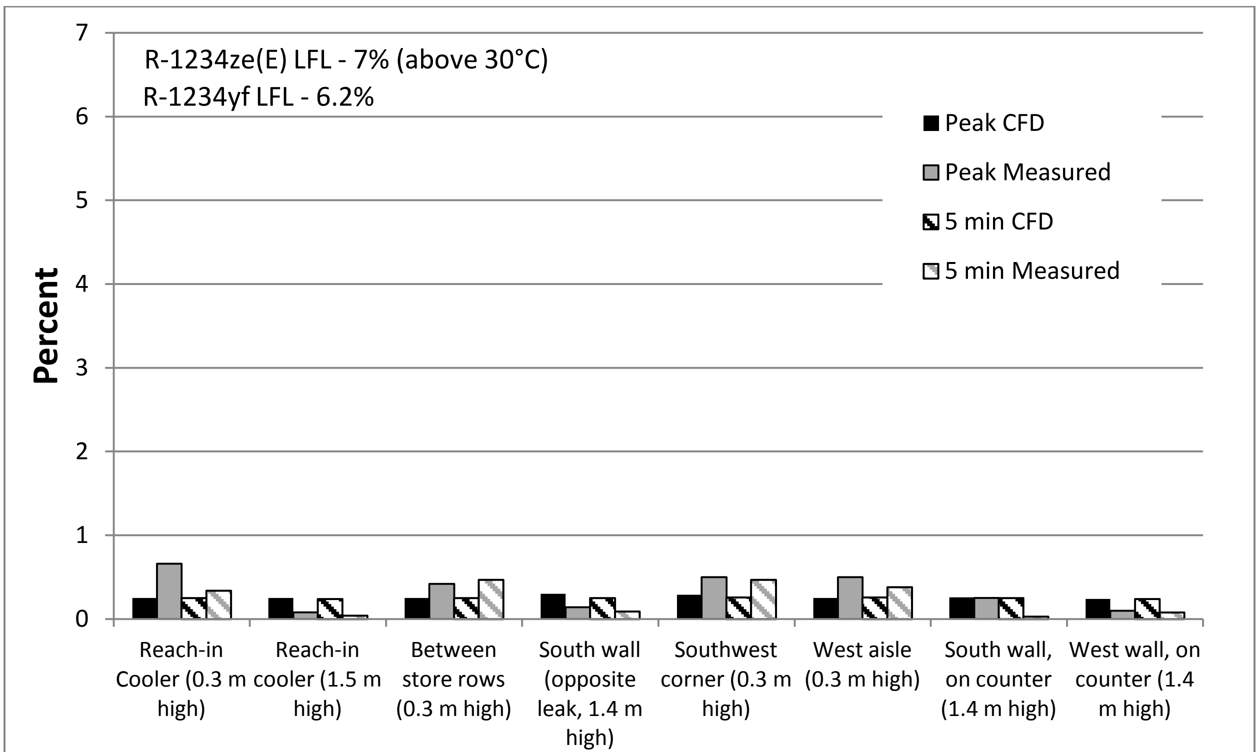


Figure 3.41 Comparison of CFD Modeling and Experimental Testing Results, R-1234ze(E), Convenience Store Scenario

4 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 the 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 system 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.[5] 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).

4.1 Fault Tree Development

Appendix B contains FTs developed to assess the potential ignition risks of the refrigerants under study. One complete 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 two additional parameters addressing the flammability of R-1234ze(E) only at elevated temperature and humidity. The FTs were adapted from those published by Gradient (2009) for heat pump systems and were revised to incorporate data on cooler configuration, system 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. 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 three FTs (FT1 through FT3) relate to leaks from installed cooler systems in three different commercial locations (*i.e.*, a convenience store [FT1], a lunch counter [FT2], or a kitchen in a small restaurant [FT3]). For the convenience store and restaurant kitchen, the trees have four major branches relating to a large or small leak in a reach-in or walk-in cooler. For the lunch counter, there are only two branches corresponding to a large or small leak in a reach-in unit because a walk-in unit would not be expected in a facility of this limited size.[6] For the walk-in units two subcases were considered, a release where the cooler door is closed and one where it is open during the leak or shortly after it occurs. In the first subcase, the refrigerant concentration in the cooler may more readily reach the LFL due to the smaller volume available but the only likely ignition source would be a spark from the cooler system. In

[5] 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 that 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.
[6] A whole range of permutations on cooler type, cooler size, facility type and facility size are possible; the goal of the risk assessment was to estimate risks on likely scenarios.

the second subcase with the door open, the refrigerant concentration may be lower due to dilution in the kitchen air but there are more potential ignition sources possible, including open flames associated with a gas cooktop or pilot light as well as more potential electronic equipment. The walk-in cooler sections in FT1 and FT3 also have branches relating to an outside condenser. In this case, the potential ignition source is an electrical fault (*i.e.*, spark of feed through plug failure) in the condensing unit itself. This section of the fault tree also considers whether the plume of refrigerant exceeds the LFL outside of the condenser so that refrigerant ignition might impact other structures.

In each FT branch we consider: 1) the probability that a flammable concentration of refrigerant will exist in the setting in question; and 2) the probability that a sufficient ignition source is present in the room to ignite the refrigerant. As noted above, two types of leaks were assessed: a small leak due to corrosion or fatigue of small tubing and a large leak resulting from the rupture of larger components. The former leaks are more frequent but are less likely to release refrigerant at a large enough rate to produce flammable concentrations. Regarding the probability of a sufficient ignition source being present, both electronic and flame sources were considered as appropriate. Electronic sources could include sparks from wiring shorts, faulty appliances, or similar. Flame sources could include unshielded pilot lights, gas burners, butane lighters, or matches used to light tobacco products. It should be noted, however, that Arthur D. Little, Inc. (1998) found that 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.

FT-R involves a refrigerant leak during a repair situation. Separate branches are associated with reach-in and walk-in units because these have different repair frequencies. The branch for the reach-in units considers three 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 service person recharges a system, then uses a propane torch to check for a leak; and 3) if the service person vents or improperly recovers refrigerant from a system, producing a flammable concentration in the air, then uses a match to light a cigarette. For the walk-in units, the analysis also considers the possibility of brazing a joint outside where a condensing unit might be located.

4.2 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. Information on the configuration, typical refrigerant charges and likely leak locations for commercial reach-in and walk-in cooler locations was obtained from Original Equipment Manufacturer (OEM) representatives. A number of values related to system faults (*e.g.*, probability of leaks) were from literature sources (Ayers, 2000; Colborne and Suen, 2004; Unilever, 2008; Gradient, 2009). For example, 10^{-5} was used as the probability that a line rupture occurs in a small leak in a reach-in unit based on commercial refrigeration equipment monitoring data reported in Ayers (2000) as cited by Colborne and Suen (2004). While this value is nearly an order of magnitude higher than values reported for ice cream freezers in Unilever (2008), this was considered a reasonable estimate given the design differences between reach-in coolers and ice cream freezers. Probabilities concerned with the potential for flammable refrigerant concentrations in various locations were assigned based on the results of the CFD modeling. Specifically, using the plots and screen captures of video simulations as shown in Figures 3.4 through 3.20, maximum concentrations for different scenarios were estimated. Failure probabilities for electronic components were obtained from established sources, such as the United States Nuclear Regulatory Commission (US NRC) *Fault Tree Handbook* (US NRC, 1981) or the United States Department of Defense Reliability Information Analysis Center (RIAC) electronic parts reliability database (RIAC, 2014). Failure rates for wire faults ($2.6 \cdot 10^{-3}$ per yearr) and for electrical feed through connectors ($4 \cdot 10^{-5}$ per year) were queried from these databases and used to assign probabilities to spark occurrence for various fault tree scenarios. 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 cooler design and operation. Table B.1 in Appendix B describes all of the probabilities used in the FTA along with their associated rationales.

As an example of FT parameterization, consider the fault tree branch related to an ignition in the outside condenser of a walk in unit in a convenience store (FT1). In this case, the feed through ignition event for the large R-1234ze(E) leak in the outside condenser for the convenience store scenario involves inputs from several of the different sources noted above. The probability of a feed through ignition event, Gate 670 in FT1 for R-1234ze(E), is the product of the probability of (1) the failure of the electrical feed through plug, (2) the feed through plug energy being sufficient to ignite the refrigerant, (3) the feed through fault occurring when a flammable concentration is present, (4) release turbulence not preventing refrigerant ignition, (5) wind not preventing propagation flammable concentration forming, (6) the blower being off, and (7) the jet of ignited refrigerant extending outside of the condenser unit to adjacent structures. The RIAC NRPD (2011) database was used to determine failure rates for electrical feed through connectors, and an operating time of 20% was assumed, leading to a calculated probability of electrical feed plug failure (1) of 8×10^{-6}. Because a feed through plug failure would have sufficient energy to ignite all of the refrigerants in this study (*i.e.*, the plug would get extremely hot), the probability for (2) was universally set to 1. However, the feed through plug failure may not necessarily occur when the refrigerant is in the flammable range: when first released, the refrigerant will likely be above the flammable limit and by the time the refrigerant reaches the flammable range, it is possible the plug may have been cooled by the refrigerant. Thus, a value of 0.75 was conservatively chosen for (3). R-1234ze(E) and R-1234yf have very unstable flame properties, so a modest amount of turbulence could prevent flame propagation; a probability of 0.05 that the flame is stable enough to exist more than a fraction of a second was used for (4). A value of 1.0 was used for R-32 which has a much more stable flame when ignited. Data from NOAA indicate that still air conditions prevail in the U.S. about 6% of the time, so a probability of 0.06 was used in this case. It was assumed that the blower would operate about 30% of the time and a probability of 0.3 assigned to (6) because walk-in units cycle on and off during the day and may not cycle on at all at night. Finally, the probability of a flame extending outside of the condenser unit (7) was given a value of 0.01 because CFD modeling showed that there was a low probability of flammable concentrations outside the condenser unit, even when enclosed by a 4-walled structure (see Figure 3.20). In general, research and analysis similar to the above was used for the inputs in all of the probabilities used in the FTA, as detailed in Appendix B.

4.3 FTA Results

Table 4.1 shows the results of the FTA. Ignition risks across the different scenarios ranged from 10^{-10} to 10^{-13} for R-1234ze(E), from 10^{-9} to 10^{-12} for R-1234yf, and from 10^{-9} to 10^{-11} for R-32. The potential for ignition at the outside condenser due to a feed through plug failure was typically a major contributor to the overall risk for the two scenarios where a walk-in cooler/outside condenser was included (*i.e.*, the convenience store and restaurant kitchen). An exception to this case was a R-1234yf release in the restaurant kitchen where the instability of R-1234yf flames in a turbulent release jet reduced outside ignition risk but interior risks were similar to those of R-32.[7] The other ignition source for the outside condenser (a spark due to a short) was a negligible contributor to overall risk.

[7] Turbulence of the release is not significant in the indoor scenarios because the ignition sources (*e.g.*, cooktops) are not located near the release point.

Among the indoor portions of the convenience store and restaurant kitchen scenarios, reach-in and walk-in cooler leaks contributed similarly to overall risk for R-32 and R-1234yf. Because the lunch counter did not involve a walk-in cooler, the risks for this scenario were less than those for the convenience store and restaurant kitchen. Of the three building scenarios, the restaurant kitchen was associated with the highest risks, largely due to the greater presence of potential ignition sources relative to the lunch counter or convenience store. Considering the three refrigerants, the lower risk for R-1234ze(E) is attributable to its potential to be ignited only at elevated temperature (>30°C) and humidity, a condition that would be very rare in convenience stores and lunch counters although somewhat more likely in a small restaurant kitchen. This property is not relevant for the outside feed through plug failure scenario, where the fault is expected to produce very high temperatures. R-32 and R-1234yf produce similar risks indoors where ignition sources are far from the leak location; outdoors, the feed through plug failure scenario dominates, and there the leak location and ignnition source are co-located and the impact of release turbulence on flame stability is more important (R-1234yf ignition being more likely to be affected by release turbulence).

In the repair scenario for R-32 and R-1234yf, the risk was dominated by the walk-in unit and the branch involving improper recovery of refrigerant with subsequent ignition by a smoking-related match or lighter. Risks for R-1234yf are slightly lower because there would be a greater incentive to recover this refrigerant due to its higher cost. For R-1234ze(E), the branch relating to improper use of a gas torch to test for the refrigerant leak was also a significant contributor to overall risk, largely because this scenario involves an indoor situation where elevated temperature and humidity necessary for R-1234ze(E) ignition may be more likely.

Table 4.1 Results of FTA

Scenario	Fault Tree	Risk of Refrigerant Ignition (Events per Unit per Year)		
		R-32	R-1234ze(E)	R-1234yf
Convenience Store Scenario	1	1×10^{-9}	6×10^{-11}	2×10^{-10}
Inside event[(1)]				
Reach-in		8×10^{-11}	4×10^{-13}	8×10^{-11}
Walk-in		6×10^{-11}	3×10^{-13}	6×10^{-11}
Outside event[(2)]		1×10^{-9}	6×10^{-11}	6×10^{-11}
Lunch Counter Scenario[(3)]	2	2×10^{-10}	7×10^{-13}	2×10^{-10}
Restaurant Kitchen Scenario	3	3×10^{-9}	3×10^{-10}	2×10^{-9}
Inside event				
Reach-in		6×10^{-10}	2×10^{-10}	6×10^{-10}
Walk-in		9×10^{-10}	4×10^{-10}	9×10^{-10}
Outside event		1×10^{-9}	6×10^{-11}	6×10^{-11}
Repair Scenario	R	1×10^{-11}	2×10^{-13}	4×10^{-12}

Notes:
FTA = Fault Tree Analysis.
1. Risks for the small and large leaks are combined in these results.
2. Risk associated with refrigerant ignition in outside condenser (due to feed through plug failure).
3. The lunch counter has only reach-in units and therefore no outside condenser (associated with a walk-in unit).
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.

4.4 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 are far below risks of other hazards that are commonly accepted by the public. For example, the overall risks of refrigerant ignition – 10^{-9} to 10^{-11} for R-32, 10^{-9} to 10^{-12} for R-1234yf, and 10^{-10} to 10^{-13} for R-1234ze(E) – are well below the risk of a significant commercial structure fire from any cause (2×10^{-2} per building 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, which would minimize contact with leaked refrigerant.

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

Relevant Hazard	Risk per Person or Building per Year[a]	Source
Slip/fall injury requiring medical treatment	3×10^{-2}	CDC (2012)[b]
Commercial building fire significant enough to warrant fire department response	2×10^{-2}	NFDC (2013)
Commercial building fire resulting from cooking activity	3×10^{-3}	NFDC (2013)
Fatal injury at work (all occupations)	4×10^{-5}	NSC (2004)
Injury at work due to fires or explosions	8×10^{-6}	NSC (2011)
Bodily injury during use of fireworks	4×10^{-5}	CPSC (2005)[c]
Damage to the home due to fireworks-associated fire	1×10^{-5}	NFPA (2011); US Dept. of Commerce and US Census Bureau (2001)[d]
Cooler refrigerant ignition, R-32	10^{-9} to 10^{-11}	Current Analysis
Cooler refrigerant ignition, R-1234yf	10^{-9} to 10^{-12}	Current Analysis
Cooler refrigerant ignition, R-1234ze(E)	10^{-10} to 10^{-13}	Current Analysis

Notes:
FT = Fault Tree; R-1234yf = 2,3,3,3-Tetrafluoropropene; R-1234ze(E) = Trans-1,1,1,3-Tetrafluoropropene; R-32 = 1,1-Difluoromethane.
(a) Assumes only one chiller system per building.
(b) The total number of unintentional falls treated in US hospitals in 2009 divided by the US population in 2009 (305 million).
(c) Based on hospital emergency room data. Assumes all individuals have an equal likelihood of using fireworks.
(d) Data for 2000 on the number of home fires related to fireworks use divided by the number of US housing units in 2000.

4.5 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 key inputs to the FTs (provided in Appendix B) were changed to other plausible values, and the resulting frequency of the top event (*i.e.*, refrigerant ignition) was then calculated. The new adverse event frequency was then compared to the value determined *via* the original inputs. To conduct the sensitivity analysis, all of the parameters were reviewed and those which were considered uncertain and could potentially change by a significant amount were assigned new, plausibly higher values. Parameters that were considered uncertain were those based on expert judgment and/or extrapolation from certain test conditions to others. The sensitivity analysis was carried out for FT3 and FTR focusing on the walk-in unit branches because these involved the largest risk. The kitchen scenario (FT3) was studied because it generated the highest risk while the repair scenario (FTR) was studied because it largely involved a different set of inputs.

Five different analyses were conducted. We first considered alternative parameters for the indoor portion of the walk-in cooler section of FT3. Six inputs considered to be particularly uncertain were increased by up to one order of magnitude. We then considered the outdoor portion, particularly the failure of the feed through plug which was a significant contributor to overall risk. In this analysis we increased the risk of a feed through plug failure by an order of magnitude and also decreased the effect of several potential mitigating variables such as the potential dispersive effect of wind. For the third analysis, we modified a number of parameters associated with the repair scenario, notably the inputs related to ignition sources such as smoking or the use of a propane torch to check for leaks. For the fourth analysis we decreased the probability that refrigerant would exist in a flammable concentration near any of the potential ignition sources by an order of magnitude. This analysis was based on the fact that none of the CFD modeling showed flammable refrigerant concentrations forming, even with fairly small spaces and still air. Thus our base assumption that flammable concentrations could form in particularly crowded spaces may have been overly conservative and worth further evaluation. Finally, the fifth analysis considered the effect of all stoves having a gas pilot light. This analysis was requested by one of the PMS members. The parameters modified as well as the results of the analysis are shown in Table 4.3.

While the modifications shown in Table 4.3 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.*, each produced ignition risks that were still far below risks of comparison events shown in Table 4.2). It should also be stressed that the risk estimates in Table 4.3 were the result of changing base-case inputs that PMS members considered reasonable. They could possibly represent conditions for specific installed units but do not reflect the average risk across the entire cooler population (which is the focus of this risk assessment). The results of this exercise do suggest that the reliance on expert opinion to derive particular FT inputs did not significantly influence the results of the assessment.

Table 4.3 Sensitivity Analysis Results

Input Modification	Value change	Risk of Refrigerant Ignition (Events per Unit per Year)			Comment
		R-32	R-1234ze(E)	R-1234yf	
1. Base Case Results for FT3 (Walk-in branch, small leak)		8×10^{-10}	3×10^{-10}	5×10^{-10}	Risks increased 1-2 orders of magnitude but still well below comparison risks.
Alternative Parameter Set		4×10^{-7}	5×10^{-8}	4×10^{-7}	
Line rupture occurs (small leak, large leak)	10-fold increase				
Insufficient ventilation in kitchen	0.05 to 0.2				
Ambient conditions such that R-1234ze(E) is flammable	0.4 to 0.7				
Refrigerant in flammable range reaches flame/pilot light ignition source	10-fold increase				
Spark has sufficient energy to ignite refrigerant	0.01 to 0.1				
Spark occurs in area of flammable concentration	0.02 to 0.2				
2. Base Case Results for FT3 (Walk-in branch, small leak in condenser)		1×10^{-9}	6×10^{-11}	6×10^{-11}	Risks increased 1-2 orders of magnitude but still well below comparison risks.
Alternative Parameter Set		4×10^{-8}	2×10^{-9}	2×10^{-9}	
Feed through plug failure occurs	10-fold increase				
Still air, no wind conditions	0.06 to 0.2				
Ambient conditions such that R-1234ze(E) is flammable	0.4 to 0.6				
Condenser spark occurs when flammable concentration present	0.1 to 0.25				
Box around electronics does not prevent flame propagation	1E-4 to 1E-3				
3. Base Case Results for FTR (Walk-in branch)		8×10^{-12}	3×10^{-13}	3×10^{-12}	Notable increase in risk although all changes are unlikely to occur at same time. Risks still below comparison values.
Alternative Parameter Set FTR		8×10^{-9}	2×10^{-10}	8×10^{-9}	
Probability a walk-in unit is serviced per year	0.01 to 0.05				
Fraction of all service calls involving a large or moderate leak	0.01 to 0.1				
Service person routinely uses a torch to test for leaks	0.005 to 0.05				
Service person believes refrigerant is non-flammable	1E-4 to 1E-3				
Indoor conditions such that R-1234ze(E) is flammable	0.075 to 0.25				
Outdoor conditions such that R-1234ze(E) is flammable	0.4 to 0.6				
Sufficient refrigerant remains in system during brazing activity	100-fold increase				
Service person smokes during repair	0.005 to 0.05				
Still air, no wind conditions	0.06 to 0.2				
4. Base Case Results for FT3 (Walk-in branch, small leak)		8×10^{-10}	3×10^{-10}	5×10^{-10}	Limited effect
Decrease probability refrigerant in flammable range reached ignition sources	10-fold decrease	7×10^{-11}	3×10^{-11}	7×10^{-11}	
5. Base case results for FT3 (Walk in branch, small leak)		8×10^{-10}	3×10^{-10}	5×10^{-10}	Minimal change
Increase probability stove has pilot light	0.76 to 1.0	9×10^{-10}	4×10^{-11}	9×10^{-10}	

Notes:
FTA = Fault Tree Analysis; R-1234yf = 2,3,3,3-Tetrafluoropropene; R-1234ze(E) = Trans-1,1,1,3-Tetrafluoropropene; R-32 = 1,1-Difluoromethane.

5 Data Gaps

This risk assessment was geared to address a specific set of questions concerning the use of ASHRAE/ISO 2L refrigerants in commercial reach-in and walk-in cooler systems. The scope of the risk assessment was constrained by the original proposal request, in terms of what could reasonably be investigated for the allowed cost and timeframe. The assessment was also limited by the data available concerning cooler leak rates, installation, and repair practices. There are a number of data gaps or areas of uncertainty that 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 system designs.** Most data on refrigerant leak rates for units in commercial settings found in the literature review represented aggregate values for entire industries, rather than device-specific values. Data from UK-based Parasense collected in 2000, cited in related risk assessments, are no longer accessible from Parasense and are only known through secondary citations. Further, historical data from the Department of Defense were often based on proprietary sources, and details regarding the specifics of data collection were scarce. The probabilities for air handler and inlet piping leaks were obtained by Arthur D. Little, Inc. and published in the Arthur D. Little, Inc. (1998) study. Steering committee members reviewed these estimates and determined that they would provide an appropriate estimate of leak frequencies in current operating systems.
2. **Limited data on ignition studies of these refrigerants with various possible commercial sources.** The AHRI PMS spent a considerable amount of time discussing whether different types of commercial 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 while testing for other applications. A limited amount of data was obtained by Arthur D. Little, Inc. (1998), although the number of sources was limited (*i.e.*, high energy arcs and pilot lights). Although we are aware of one technical report along these lines (ASHRAE/Navigant, 2012), this document did not provide quantitative information that could be used in the FTA.
3. **Future design changes in cooler units.** The purpose of the risk assessment is to examine the potential risks should A2L refrigerants be used in commercial cooler units in the future. Although in some cases it was possible to project future conditions (*e.g.*, greater recovery potential due to higher refrigerant cost, greater awareness about potential refrigerant flammability) it is likely that unanticipated advances in cooler design or repair could substantially alter the potential for refrigerant leaks or ignition. Given that OEMs intentionally design systems so as to increase equipment reliability and safety, such unforeseen advances would presumably produce risks that are lower than those estimated here.

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-134a and R-404A 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 commercial cooler applications is different because individuals trapped by a vehicle collision cannot avoid HF exposure, but an analogous situation is unlikely to occur in a commercial 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 commercial settings.
2. **Assessment of the effect of humidity on refrigerant ignition.** We included humidity as a factor in the FTA. 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); however, the degree of change is relatively limited (*e.g.*, a few tenths of percent, in terms of the LFL). In the FTA, we assumed that the overall probability of R-1234ze(E) ignition could be increased by 50%, due to the impact of high humidity on lowering the LFL below that measured at test conditions (30°C or 86°F). This may overestimate the effect and could lead to an overestimation of risk.
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 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 of the current analysis was to determine whether use of 2L refrigerants in commercial reach-in and walk-in cooler systems, *in principle*, was worth further exploration and study. Based on the current findings, blend-specific risk assessments would be appropriate.

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

6 Conclusions

This risk assessment was aimed at evaluating the potential risks of using mildly flammable refrigerants (ASHRAE class 2L) in commercial refrigeration systems. Although widespread use of flammable refrigerants in a commercial setting would represent a change in industry practice over the past 60 or more years, addressing concerns regarding the GWP potential of fluoroalkanes such as R-134a or R-404A 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 commercial 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 refrigeration 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. Risks based on typical cooler design and installation, estimated at 10^{-9} to 10^{-11} events per unit per year for R-32, 10^{-9} to 10^{-12} events per unit per year for R-1234yf, and 10^{-10} to 10^{-13} events per unit per year for R-1234ze(E), are well below the overall risk of commercial structure fires from any cause (2×10^{-2} per home per year).

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 commercial refrigeration systems. Based on CFD modeling, experimental testing, and FTA, the risk assessment indicates that the overall average risks associated with the use 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.

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APPENDIX A
Hughes Associates Inc. Detailed Results

HUGHES ASSOCIATES

Refrigerant Concentration Tests
Test Report

Prepared for

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August 13, 2014

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1. INTRODUCTION

New candidate refrigerants have been developed to reduce the global warming potential of refrigerants in commercial refrigeration systems. The developed refrigerants tested were HFO-1234ze and HFC-32. The developed refrigerants have global warming potentials of less than 450 (CO_2=1). The currently used refrigerant, R-410A, has a global warming potential of ~1,860.

As the developed refrigerants are slightly flammable, dispersion models were developed to evaluate the potential for flammable conditions to develop in a commercial setting resulting from a variety of leakage scenarios and geometric parameters arising from commercial refrigeration and chillers. In order to validate the dispersion models developed, a series of tests was conducted. These tests consisted of measuring the refrigerant concentration resulting from the discharge of the refrigerants in a commercial setting for a few of these conditions. The results will be compared to the dispersion model results for the same leakage scenario and geometric parameters.

2. APPARATUS

2.1. Test Enclosure

This test series was conducted in a commercial mock-up constructed inside the 312 m^3 (11,000 ft^3) test enclosure at the Baltimore, MD facilities of Hughes Associates (Hughes). The test enclosure was 10 x 10 m (32.8 x 32.8 ft) and constructed with gypsum wall board over a metal stud frame. It had a suspended tile ceiling 3.1 m (10.3 ft) above a raised floor consisting of 0.6 m (2 ft) steel tiles supported by an aluminum and steel framework. The enclosure had two doors at opposing diagonal corners and had four 1.2 x 2.4 m (4 x 8 ft) polycarbonate windows for observation. It was connected to two exhaust fans, one exhausted from the ceiling near the southern wall of the enclosure and the other from the southern wall of the enclosure. The sub-floor was be sealed to prevent migration of the refrigerant into the sub-floor area during these tests.

The test enclosure was arranged as illustrated in Figure 1 through Figure 10 to create the desired settings. The dimensions of these sub-enclosures are given in Table 1. The Luncheon Counter, Convenience Store, and Café Seating Area all include the Restroom in the dimensions. The ceiling of these mock-ups consisted of a suspended ceiling at an elevation of 2.4 m (8 ft) above the floor. The refrigerant was discharged from one of three locations to simulate the loss of refrigerant from the reach-in type coolers or the walk-in freezer as included in the setting. Cardboard boxes, nominally 45 cm (1.5 ft) cubes, were arranged in the settings to represent the volume occupied by kitchen appliances, store shelves, and other clutter. Metal cabinets with dimensions of 0.7x0.7x2.1 (2.5x2.5x6.9 ft) were used to simulate the reach in coolers in the convenience store and luncheon counter settings with two and four cabinets each, respectively. During the Luncheon Counter tests, the interior doors were taped around the floor and door frame to reduce leakage.

The enclosure was purged after each test utilizing the 56 x 51 cm (22 x 20 in.) vent in the southern wall. This vent was connected to variable speed fan with a maximum flow rate of 285 m^3/min (10,000 CFM). The access doors were opened to allow for the flow of make-up air into the enclosure during the purge period.

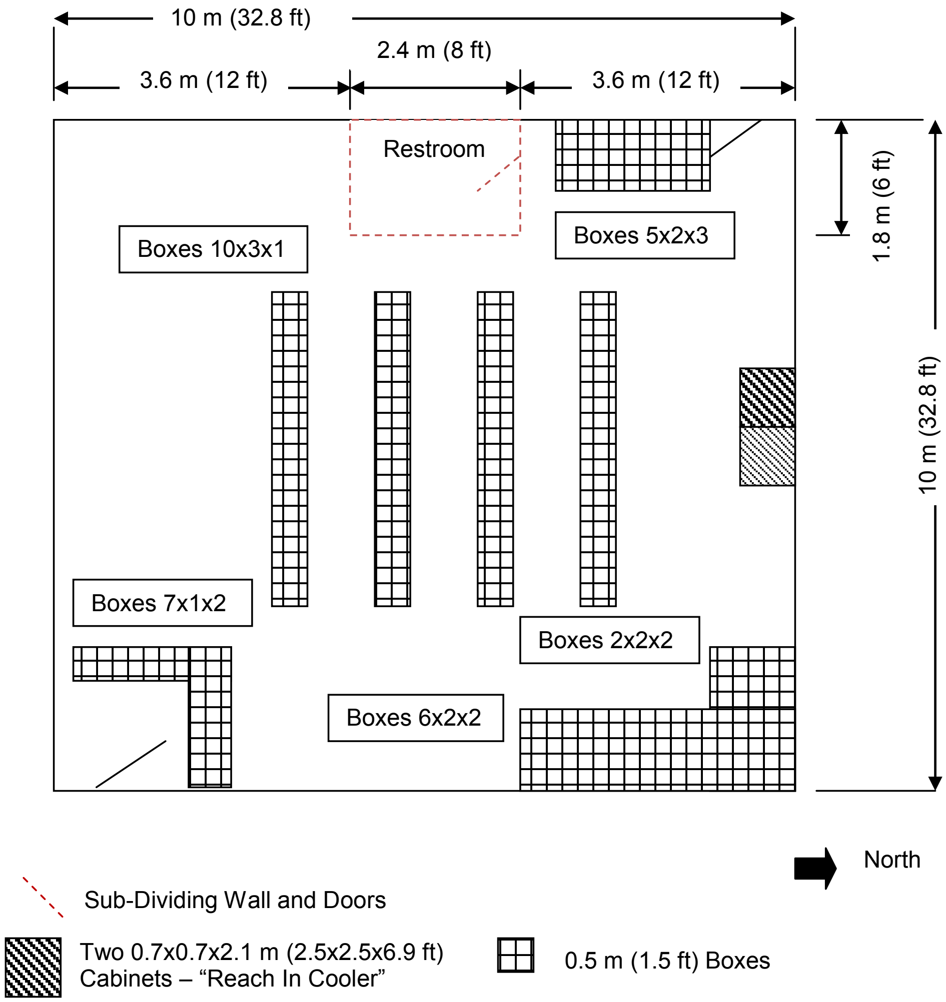


Figure 1 – Convenience Store Scenario Diagram

Figure 2 – Convenience Store Scenario Setup (Southeast Corner Looking Northwest)

Figure 3 – Convenience Store Scenario Setup (Northwest Corner Looking East)

Figure 4 – Convenience Store Scenario Setup (Northeast Corner Looking South)

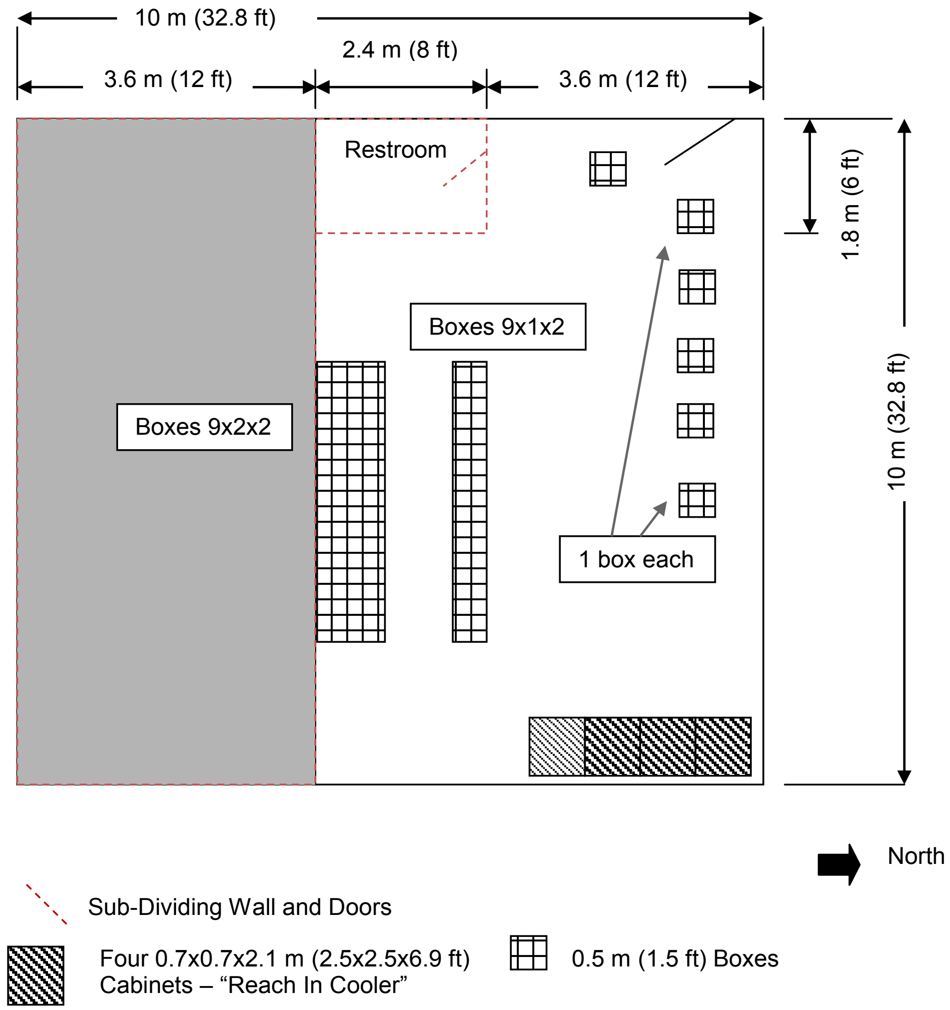


Figure 5 – Luncheon Counter Scenario Diagram

Figure 6 – Luncheon Counter Scenario Setup

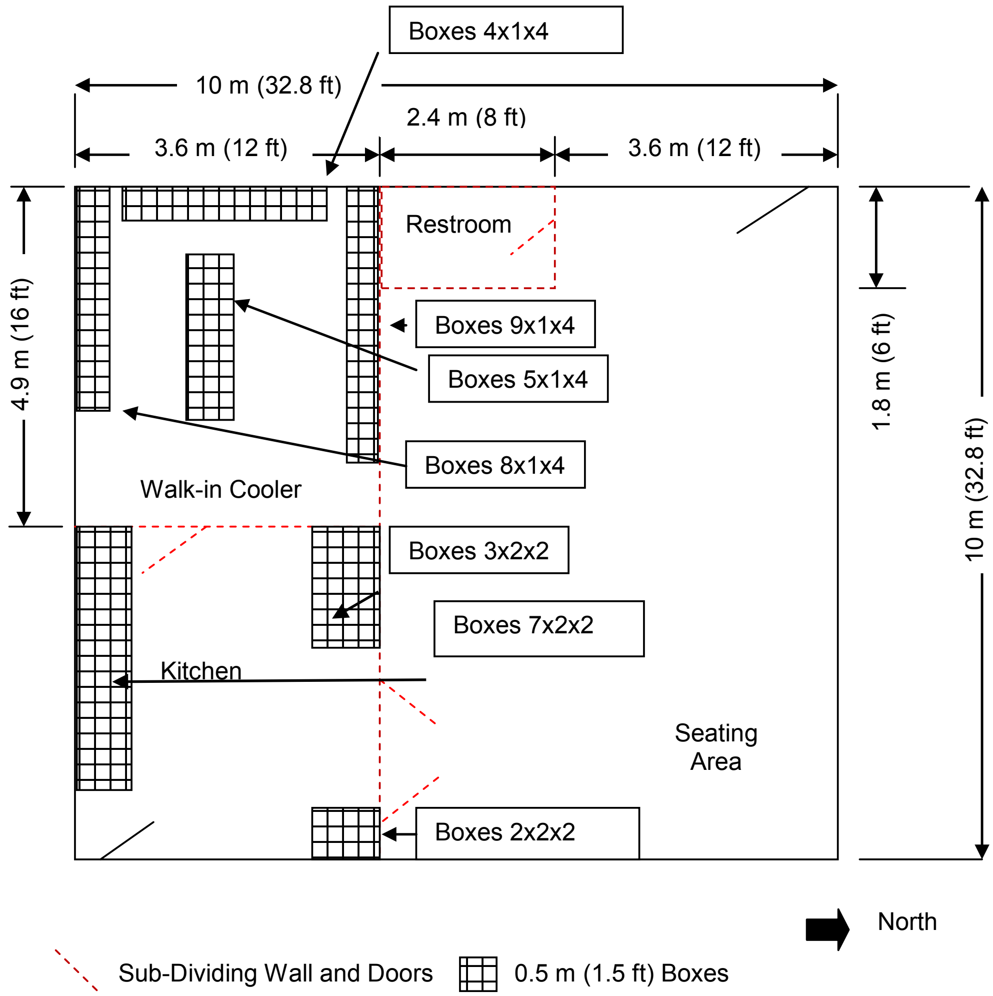


Figure 7 – Café Scenario Diagram

Figure 8 – Café Scenario Kitchen Setup

Figure 9 – Café Scenario Walk-in Cooler Setup

Figure 10 – Café Scenario Seating Area Setup

Table 1 – Enclosure and Sub-enclosure Dimensions

Enclosure/Room	Floor Area		Volume	
	m²	ft²	m³	ft³
Café Walk-in Cooler	17.8	192	43.5	1536
Café Kitchen	18.7	202	45.7	1614
Café Seating Area	63.4	683	154.7	5462
Luncheon Counter	63.4	683	154.7	5462
Convenience Store	100.0	1076	243.8	8611

2.2. Refrigerants

Physical properties of the developed refrigerants, the currently used refrigerant (R-410A) and the refrigerant being phased out (R-22) are given in Table 2 [1-7]. R-22 was the predominate HVAC refrigerant in heat pumps, air conditioners and coolers. It is the subject of a production ban due to its non-zero ozone depletion potential as part of the amendments to the Montreal Protocol. R-410A has been used to fill this need in new equipment, but cannot be used as a retrofit. It also has a high global warming potential which may lead to restrictions on use or production in the future. The developed refrigerants are slightly flammable unlike the refrigerants they would replace that are non-flammable.

HFO-1234ze and HFC-32 were utilized during these tests. HFO-1234yf was not included to save time as it was expected to yield similar results to those obtained with HFO-1234ze. During the tests with the Café Scenario, 4.5 kg (10 lb) of refrigerant, either HFC-32 or HFO-1234ze, were discharged. This charge mass was representative of that utilized in a large walk-in refrigerator. During the tests with the Luncheon Counter Scenario, 0.9 kg (2 lb) of refrigerant was discharged representing the mass associated with a small reach-in cooler. During the tests with the Convenience Store Scenario, 2.3 kg (5 lb) of refrigerant was discharged representing the charge mass associated with a larger reach-in cooler.

The refrigerant was discharged from a 12 L (0.42 ft^3) steel cylinder with a 13.6 kg (30 lb) capacity through 9.5 mm (3/8 in.) diameter copper tubing with a length of 15.2 m (50 ft). The flow was controlled by a manually operated quarter turn ball valve located downstream of the cylinder valve. The end of the tube pointed in the desired direction at either 1.8 m (6 ft) above the floor inside the walk-in cooler of the Café Scenario or 2.1 m (7 ft) above the floor on top of the reach-in coolers of the Luncheon Counter and Convenience Store Scenarios. The final bend in the tubing was a minimum of 0.3 m (1 ft) from the end of the tube. Three orifice sizes were used during testing: 9.5 mm (0.375 in), 3.2 mm (0.125 in), and 1.6 mm (0.063 in). As shown in Figure 11, the open end of the tubing created the 9.5 mm orifice, and adapters were installed at the end of the tubing to reduce the orifice size for the 3.2 mm and 1.6 mm orifice sizes. The discharge locations are shown in Table 3 and the nominal discharge tubing layout is shown in Figure 12 through Figure 14.

Table 2 – R-22, R-410A and Developed Refrigerant Properties

		R-22	R-410A (50:50 Blend)				
Property	**Units**	**HFC-22**	**HFC-125**	**HFC-32**	**HFO-1234ze**	**HFC-32**	**HFO-1234yf**
Formula		$CHClF_2$	C_2HF_5	CH_2F_2	$CF_3CH=CHF$	CH_2F_2	$CF_3CF=CH_2$
Molecular Weight		86.476	120.02	52.00	114.00	52.00	114.00
Critical Temperature	[°C]	96.0	66.3	78.5	109.4	78.5	94.8
	[°F]	204.81	151.3	173.2	228.8	173.2	202.6
Critical Pressure	[kPa]	4,976	3,630	5,830	3,632	5,830	3,382
	[psia]	721.906	527	846	527	846	491
Normal Boiling Point	[°C]	-40.8	-48.2	-53.2	-19.0	-53.2	-29.2
	[°F]	-41.36	-54.7	-63.8	-2.2	-63.8	-20.6
Liquid Density @ 25°C (77°F)	[kg/m^3]	1,194	1,204	960	1,180	960	1,094
	[lb/ft^3]	74.528	75.1	59.9	73.7	59.9	68.3
Vapor Density @ 25°C (77°F) and 1 atm Press	[kg/m^3]	3.536	4.908	2.13	4.66	2.13	4.66
	[lb/ft^3]	0.221	0.306	0.133	0.291	0.133	0.291
Vapor Pressure @ 25°C (77°F)	[kPa]	1,044	1,378	1,700	490	1,700	673
	[psia]	151.4	200	247	71	247	98
Ozone Depletion Potential (ODP)	R-12=1.0	0.05	0	0	0	0	0
Global Warming Potential (GWP)	CO_2=1.0	1,700	2,800	440	6	440	4
Lower Flammability Limit @ 23°C (73°F)	[% Vol]	N/F	N/F	14	N/F*	14	6.2
Upper Flammability Limit @ 23°C (73°F)	[% Vol]	N/F	N/F	31	N/F*	31	12.3

N/F – Not flammable *Not flammable below 30°C (86°F)

(A) (B) (C)

Figure 11 – Discharge Tubing Orifice Sizes: (A) 9.5 mm tubing with no adapter; (B) and (C) with 3.2 mm and 1.6 mm adapters, respectively

Table 3 – Discharge Locations

Scenario	Discharge Location – X Coordinate		Discharge Location – Y Coordinate		Discharge Location – Z Coordinate	
	m	ft	m	ft	m	ft
Café	1.8	6	6.6	21.5	1.8	6
Luncheon Counter	3.3	11	0.9	3	2.1	7
Convenience Store	9.1	30	5.3	17.5	2.1	7

2.3. Instrumentation

The instrumentation scheme utilized during these tests was designed to monitor the flow of the refrigerant and the resultant agent concentrations in the test rooms. The locations of the instrumentation changed with the changes in leak scenario. For all measurements, the location of the origin (X = 0, Y = 0, Z = 0) is defined as the Southeast corner of the scenario used in the test. The Z coordinate of all measurements is taken from the raised subfloor of the enclosure.

2.3.1. Pressure Measurement

A pressure transducer, Omega Engineering Model PX613-1KG-5V, with a full scale range of 0-69 bar, gauge (0-1000 psig) was inserted into the refrigerant discharge line upstream of the quarter turn ball valve.

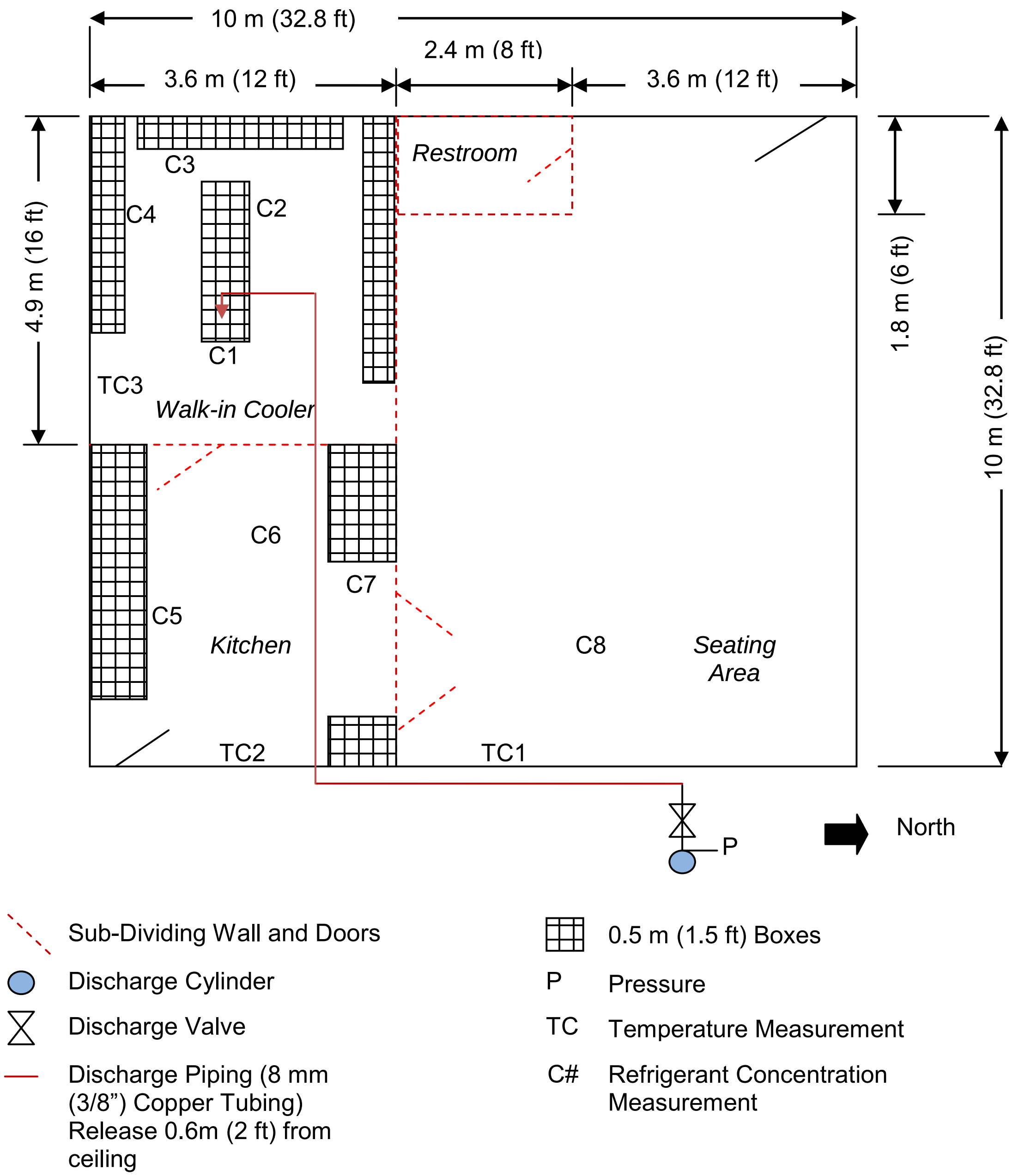


Figure 12 – Refrigerant Discharge Tubing and Instrumentation Schematic – Café Scenario

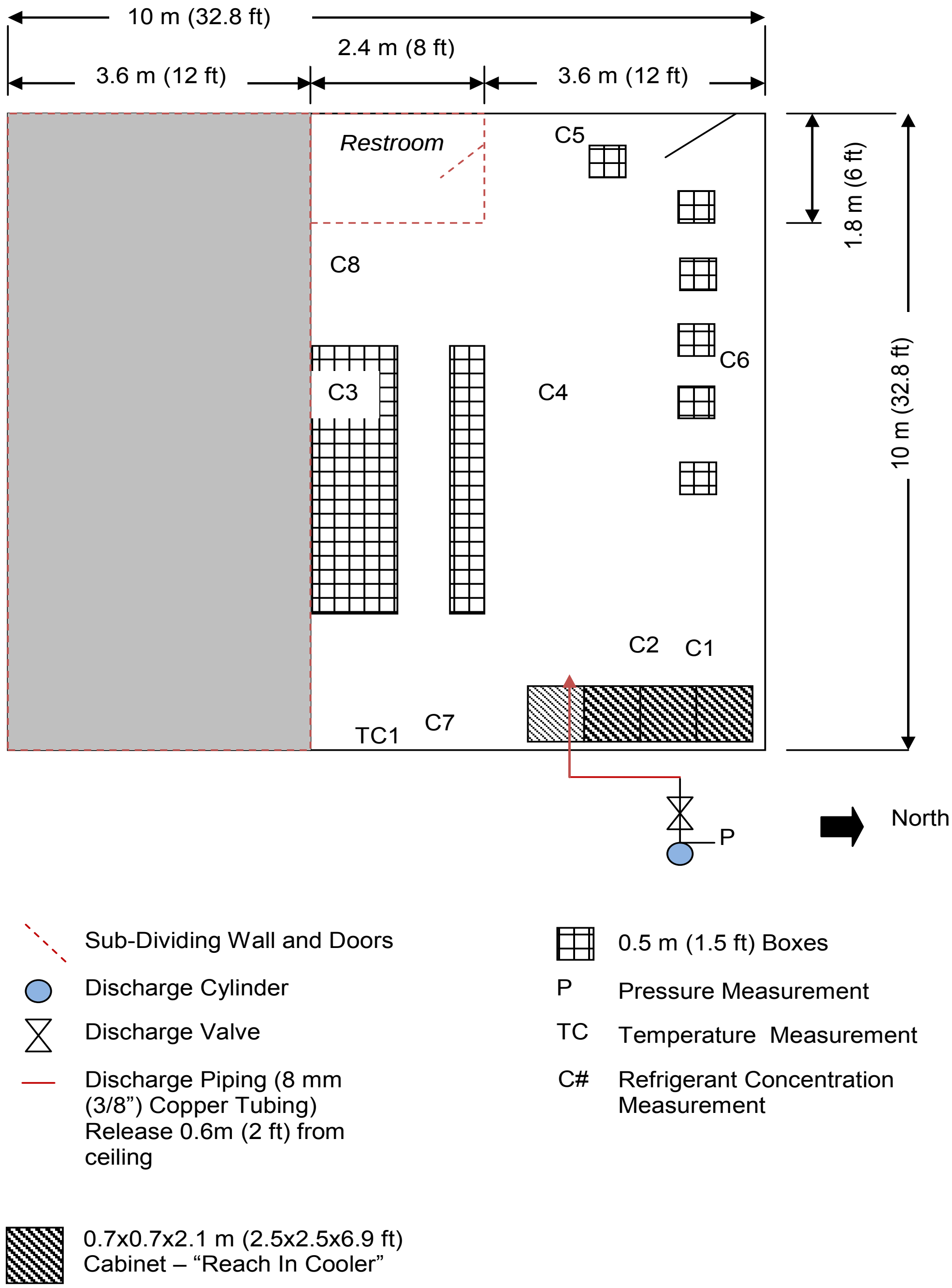


Figure 13 – Refrigerant Discharge Tubing Schematic – Luncheon Counter Scenario

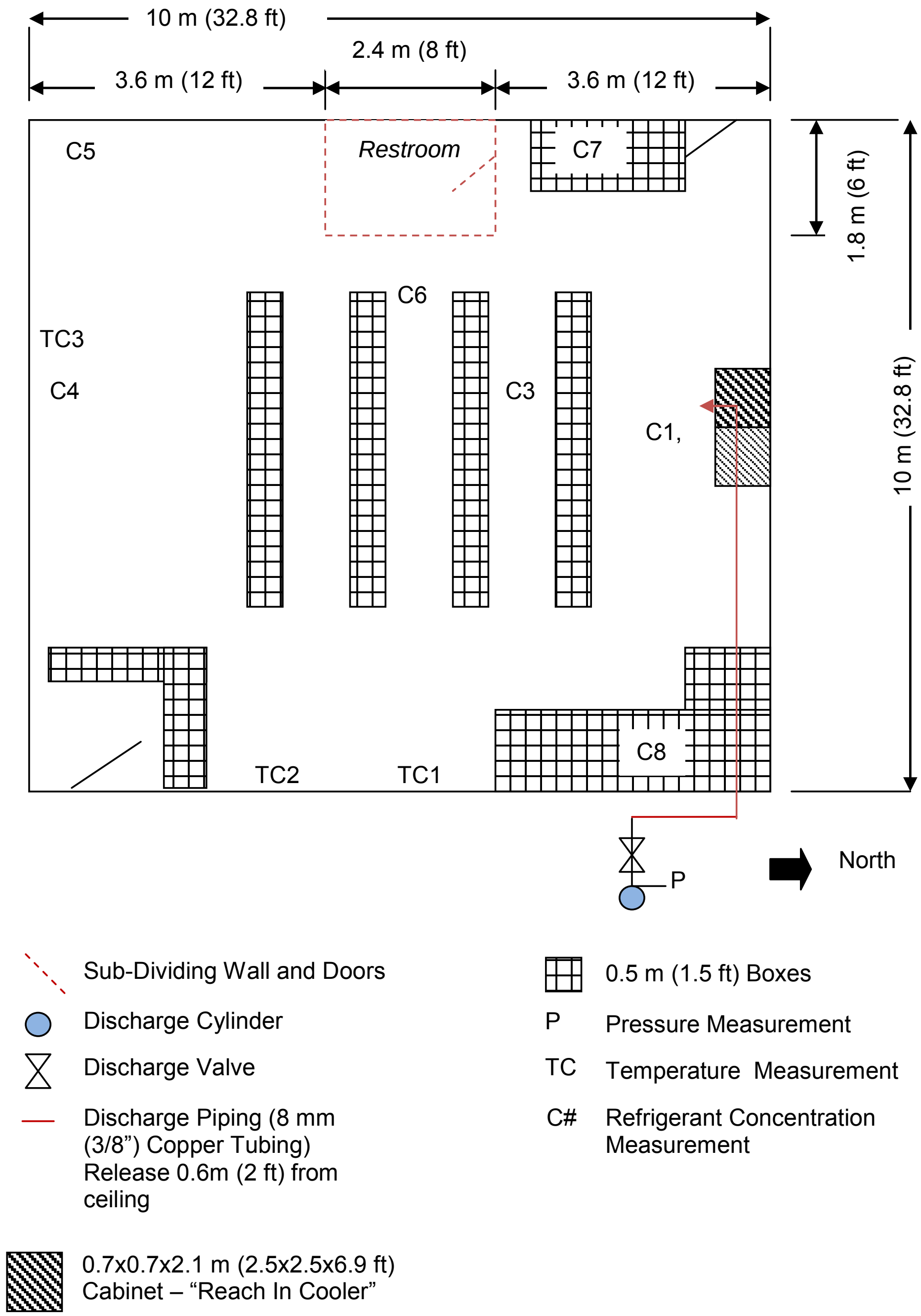


Figure 14 – Refrigerant Discharge Tubing Schematic – Convenience Store Scenario

2.3.2. Temperature Measurement

Temperature measurements were taken in three locations, as shown in Table 4. Temperature measurements were taken using Omega Type K thermocouple wire.

Table 4 – Temperature Measurement Locations

Measurement ID	TC Location – X Coordinate		TC Location – Y Coordinate		TC Location – Z Coordinate	
	m	ft	m	ft	m	ft
TC1	0	0	6.1	20	1.5	5
TC2	2.4	8	0	0	1.5	5
TC3	4	13	0	0	1.5	5

2.3.3. Refrigerant Concentration Measurement

A total of eight refrigerant sampling measurements were taken during testing. Locations of concentration measurements are provided in Table 5.

A Tri-point Instruments, Model 123, dual gas analyzer was utilized to monitor the refrigerant concentration. This analyzer works on a thermal conductivity method. The analyzer withdraws a continuous gas sample from three locations for analysis. The analyzer had a resolution of 0.22% by volume for HFC-32 and a resolution of 0.13% by volume for HFO-1234ze. The Tri-point analyzer was calibrated to measure the refrigerants to be tested by preparing a nominal 10% by volume mixture of the refrigerant and nitrogen in a 12 L (0.43 ft^3) cylinder. The calibration mixture was prepared by evacuating the 12 L (0.43 ft^3) cylinder, pressurizing it with 603 kPa, gauge (15 psig) of refrigerant vapor and then super-pressurizing the cylinder with nitrogen to 2,068 kPa, gauge (300 psig). This resulted in a gaseous mixture with a refrigerant composition of 9.4% by volume in the cylinder.

Five additional sampling points were monitored utilizing Henze-Hauck Analytik GmbH thermal conductivity based analyzers provided by Honeywell. These sensors were configured to analyze a continuous gas sample withdrawn from the sample location at a rate of 0.9 LPM. The response time of these five analyzers were reduced by adding a 0.5 LPM bypass provided by an external pump. These sensors were calibrated by Honeywell prior to these tests utilizing gas mixtures created with a gas mixing valve.

2.3.4. Leakage Measurement

A Retrotec Series 2000 door fan was utilized to measure the leakage present in the rooms of the sub-divided test enclosure prior to the start of testing. The door fan setup consisted of a calibrated fan which is mounted in the doorway of the enclosure and a digital pressure gauge. The fan was used to introduce a known flow rate of air into and out of the enclosure. The pressure gauge was utilized to measure the corresponding change in the enclosure pressure. The leakage area in the enclosure was then calculated by the following equation:

$$A_L=Q/(C_D(2g\Delta P_L/p_{air})^{0.5}) \quad \text{Eq. (1)}$$

Where A_L is the leakage area, Q is the flow rate introduced to the enclosure, C_D is the assumed discharge coefficient of the leaks present (generally set equal to 0.61), g is the acceleration due to gravity, ΔP_L is the measure pressure difference across the enclosure boundaries, and p_{air} is the density of air.

Table 5 – Gas Sampling Port Locations

Scenario	Sample Port ID	Sample Port Location Description	Sample Port – X Coordinate		Sample Port – Y Coordinate		Sample Port – Z Coordinate		Analyzer Used
			m	ft	m	ft	m	ft	
Café	C1	Walk-in Cooler	1.8	6	6.3	20.75	1.5	5	Tri-Point
	C2	Walk-in Cooler	2.0	6.5	8.5	27.75	1.5	5	Henze-Hauck
	C3	Walk-in Cooler	1.5	5	9.5	31.25	0.9	3	Henze-Hauck
	C4	Walk-in Cooler	0.5	1.5	8.5	27.75	0.9	3	Henze-Hauck
	C5	Kitchen – South Wall	0.0	0	1.7	5.5	0.9	3	Henze-Hauck
	C6	Kitchen – Center	2.7	9	1.8	6	1.5	5	Tri-Point
	C7	Kitchen – North Wall	3.7	12	3.5	11.5	0.9	3	Henze-Hauck
	C8	Seating Area	6.9	22.75	1.5	5	0.3	1	Tri-Point
Luncheon Counter	C1	Reach-in Cooler	4.0	13	1.1	3.5	0.3	1	Tri-Point
	C2	Reach-in Cooler	4.9	16	1.1	3.5	1.5	5	Henze-Hauck
	C3	South Wall	0.0	0	4.9	16	1.4	4.5	Henze-Hauck
	C4	Center	3.7	12	4.9	16	1.5	5	Henze-Hauck
	C5	West Wall	4.0	13	10.0	32.75	1.4	4.5	Henze-Hauck
	C6	North Wall	6.4	21	4.9	16	0.9	3	Tri-Point
	C7	East Wall	1.5	5	0.0	0	0.9	3	Henze-Hauck
	C8	South Wall	0.0	0	7.9	24	0.3	1	Tri-Point
Convenience Store	C1	Reach-in Cooler	8.8	29	4.9	16	0.3	1	Tri-Point
	C2	Reach-in Cooler	8.8	29	4.9	16	1.5	5	Henze-Hauck
	C3	Between Aisles	6.3	20.75	4.9	16	0.3	1	Henze-Hauck
	C4	South Wall	0.0	0	4.9	16	1.4	4.5	Henze-Hauck
	C5	Southwest Corner	0.3	1	9.7	31.75	0.3	1	Henze-Hauck
	C6	West End of Aisles	5.1	16.75	7.0	23	0.3	1	Tri-Point
	C7	West Wall	7.6	25	10.0	32.75	1.4	4.5	Henze-Hauck
	C8	East Wall	8.2	27	0.0	0	0.9	3	Tri-Point

3. PROCEDURE

Prior to the start of the test, the test scenario was set-up and the laboratory ambient conditions were recorded. The test scenario set-up consisted of configuring the room doors in the test enclosure to the desired state (open, cracked, or closed/covered), locating the refrigerant sampling tubes to the desired locations and filling the discharge cylinder with refrigerant. The cylinder was connected to the discharge line leading to the nozzle at the desired discharge location. The thermal conductivity analyzer zeroes were then checked. Electrical power to the interior of the test chamber was secured.

The data acquisition system and the thermal conductivity analyzers were started. After 2 minutes of background data, the refrigerant was discharged into the test enclosure. The instrumentation was monitored for a minimum of forty minutes beyond the start of the refrigerant discharge, or until the thermal conductivity analyzer readings return to their ambient values.

At the conclusion of the test, the data acquisition system was secured and the test enclosure purged with fresh air. The enclosure was purged for a minimum of 20 minutes before re-entry into the enclosure to prepare for the succeeding tests.

The testing procedure is summarized in Table 6.

Table 6 – Test Event Sequence

Time	Event
Prior to Start of Test	Configure Test Enclosure as Desired Close or Open Room Doors, Configure Cardboard Box Arrays within Enclosure, and Move THC Analyzer Sampling Line to Desired Locations. Electrical Power to Enclosure Interior Secured. Fill Cylinder and Connect to Desired Discharge Line.
-120 seconds	Start Data Acquisition and Start Thermal Conductivity Analyzers
0 seconds	Start Refrigerant Discharge
40 minutes	Secure Thermal Conductivity Analyzers and Data Acquisition
End of Test	Purge Test Enclosure (20 minute minimum duration)

4. RESULTS

4.1. Leakage Tests

The leakage area was determined for the entire enclosure, the Café scenario Kitchen Area, The Café Scenario Seating Area, and the Luncheon Counter Scenario sub-enclosure. The Café Scenario Walk-in Cooler area could not be tested for leakage due to doorway size constraints. The results of the leakage tests are shown in Table 7.

Table 7 – Leakage Test Results

Enclosure/Room	Pressurization Leakage Area		Depressurization Leakage Area		Average Leakage Area	
	m^2	ft^2	m^2	ft^2	m^2	ft^2
Total Enclosure	0.066	0.72	0.080	0.86	0.073	0.79
Café Kitchen	0.159	1.72	0.155	1.67	0.157	1.69
Café Seating Area	0.166	1.79	0.167	1.80	0.167	1.80
Luncheon Counter	0.090	0.97	0.103	1.11	0.096	1.04

4.2. Refrigerant Tests

A total of 21 tests were conducted. The majority of these tests, 14 tests, were conducted with the Café Scenario. Five tests were conducted with the Luncheon Counter Scenario. Two tests were conducted with the Convenience Store Scenario.

The results of these tests are presented in the follow sections by scenario utilized. Additional data for these tests are presented in Appendix A.

4.2.1. Café Scenario

A total of 14 tests were performed in the Café scenario. The discharge results of the Café scenario tests are presented in Table 8. The end of the discharge of the liquid refrigerant was indicated by an inflection in the pressure trace and 80% of the initial charge mass was assumed to be delivered by this point in estimating the average liquid flow rate. The concentration data for the initial Café scenario tests is presented in Tables 9 and 10. The 5 and 30 minute averages are calculated from the start of the refrigerant discharge. The discharge pressure measurements and the concentration measurement at point C7 during the initial six tests were affected by data acquisition errors and sensor mal-functions. Repeat tests of these initial tests were included in the subsequent set of tests conducted.

In general, the highest concentrations were observed in the center of the kitchen area (C6) which was in the direction of discharge, and in the walk-in freezer (C1, C2, C3, C4). Maximum concentrations did not exceed 3.3% by volume in any location, and 5-minute averages did not exceed 2.3% in any location. The HFC-32 tests produced greater concentrations by volume than the HFO-1234ze tests as illustrated by Figures 15 and 16. The greater cylinder pressure of the HFC-32 (approximately 100 psi) in comparison to the HFO-1234ze (approximately 30 psi) caused the HFC-32 to be discharged more rapidly as illustrated by Figures 17 and 18. Concentrations were typically greater in tests with larger orifice sizes as illustrated by Figures 15, 19 and 20. As expected, with the cooler door closed in Test 17, refrigerant concentrations were greater in the walk-in cooler, and substantially reduced from other tests outside of the cooler as shown in Figure 21.

Table 8 – Café Scenario Refrigerant Discharge Description

Test ID	Refrigerant	Orifice Size (mm)	Refrigerant Mass		Refrigerant Discharge Time		Avg. Discharge Rate (Liquid 80%)		Avg. Discharge Rate (Total)	
			kg	lb	Liquid (s)	Total (s)	kg/s	lb/s	kg/s	lb/s
6	HFC-32	9.5	4.5	10.0	48.0	72.0	0.076	0.167	0.063	0.139
1	HFO-1234ze	9.5	4.5	10.0	110.4	165.0	0.033	0.072	0.027	0.061
2*	HFO-1234ze	3.2	4.5	10.0	138.6	228.0	0.026	0.058	0.020	0.044
4	HFC-32	3.2	4.5	10.0	66.0	126.0	0.055	0.121	0.036	0.079
5	HFO-1234ze	3.2	4.5	10.0	138.0	228.0	0.026	0.058	0.020	0.044
18	HFC-32	9.5	4.5	10.0	57.0	111.0	0.064	0.140	0.041	0.090
14	HFO-1234ze	9.5	4.5	10.0	135.0	180.0	0.027	0.059	0.025	0.056
15	HFO-1234ze	9.5	4.5	10.0	111.0	201.0	0.033	0.072	0.023	0.050
16	HFO-1234ze	9.5	4.5	10.0	129.0	174.0	0.028	0.062	0.026	0.057
12	HFC-32	3.2	4.5	10.0	66.0	126.0	0.055	0.121	0.036	0.079
13	HFO-1234ze	3.2	4.5	10.0	156.0	216.0	0.023	0.051	0.021	0.046
19	HFC-32	1.6	4.5	10.0	162.0	312.0	0.022	0.049	0.015	0.032
17	HFO-1234ze	9.5	4.5	10.0	123.0	171.0	0.030	0.065	0.027	0.058

*External door to seating area inadvertently left open

Table 9 – Initial Café Scenario Test Concentration Results

Sample Location			9.5 mm (3/8in) Orifice		3 mm (1/8 in) Orifice		
			Test 6	Test 1	Test 2*	Test 4	Test 5
			HFC-32	HFO-1234ze	HFO-1234ze	HFC-32	HFO-1234ze
C2	Maximum	[%]	2.276	1.160	1.019	2.200	0.974
	5 min Average	[%]	1.667	0.648	0.470	1.548	0.479
	30 min Average	[%]	1.111	0.439	0.654	1.056	0.465
C3	Maximum	[%]	1.466	0.841	0.700	1.350	0.596
	5 min Average	[%]	1.088	0.531	0.415	1.023	0.325
	30 min Average	[%]	0.963	0.494	0.553	0.935	0.419
C4	Maximum	[%]	2.426	1.295	1.073	2.309	1.027
	5 min Average	[%]	1.797	0.745	0.572	1.740	0.543
	30 min Average	[%]	1.621	0.756	0.845	1.581	0.711
C5	Maximum	[%]	1.120	0.232	0.167	1.105	0.451
	5 min Average	[%]	0.850	0.139	0.090	0.834	0.264
	30 min Average	[%]	0.651	0.139	0.116	0.668	0.297
C6	Maximum	[%]	2.596	1.250	1.125	3.029	1.250
	5 min Average	[%]	1.905	0.852	0.845	1.936	0.880
	30 min Average	[%]	0.842	0.374	0.689	0.705	0.499
C1	Maximum	[%]	1.917	1.727	0.930	1.677	0.797
	5 min Average	[%]	1.392	0.893	0.536	1.266	0.530
	30 min Average	[%]	0.599	0.435	0.485	0.511	0.261
C8	Maximum	[%]	1.714	0.880	0.754	1.538	0.880
	5 min Average	[%]	0.317	0.000	0.038	0.330	0.030
	30 min Average	[%]	1.135	0.506	0.383	1.062	0.502

*External door to seating area inadvertently left open

Table 10 – Revised Café Scenario Test Concentration Results

Sample Location			9.5 mm (3/8in) Orifice				3 mm (1/8 in) Orifice		1.5 mm (1/16 in) Orifice	Cooler Door Closed
			Test 18	Test 14	Test 15	Test 16	Test 12	Test 13	Test 19	Test 17
			HFC-32	HFO-1234ze	HFO-1234ze	HFO-1234ze	HFC-32	HFO-1234ze	HFC-32	HFO-1234ze
C7	Maximum	[%]	3.209	1.676	1.569	1.693	2.718	1.266	2.515	0.241
	5 min Average	[%]	2.277	1.133	1.065	1.094	2.041	0.815	1.545	0.145
	30 min Average	[%]	1.835	0.853	0.810	0.805	1.779	0.786	1.779	0.127
C2	Maximum	[%]	2.440	1.242	1.197	1.243	2.094	1.019	2.239	2.599
	5 min Average	[%]	1.665	0.766	0.708	0.701	1.568	0.525	1.159	1.717
	30 min Average	[%]	1.111	0.400	0.400	0.350	1.141	0.424	1.195	0.629
C3	Maximum	[%]	2.628	0.933	1.265	1.379	1.508	0.721	2.336	2.781
	5 min Average	[%]	2.024	0.636	0.907	0.943	1.174	0.449	1.508	2.057
	30 min Average	[%]	1.670	0.523	0.740	0.733	1.146	0.476	1.651	1.261
C4	Maximum	[%]	2.524	1.348	1.232	1.369	2.187	1.027	2.330	2.751
	5 min Average	[%]	1.820	0.852	0.770	0.800	1.694	0.610	1.342	1.865
	30 min Average	[%]	1.677	0.772	0.729	0.729	1.690	0.682	1.659	1.263
C5	Maximum	[%]	1.294	0.638	0.584	0.656	1.150	0.526	1.072	0.116
	5 min Average	[%]	0.942	0.442	0.393	0.422	0.850	0.327	0.684	0.047
	30 min Average	[%]	0.748	0.339	0.318	0.347	0.742	0.334	0.731	0.067
C6	Maximum	[%]	2.812	1.500	1.500	1.500	2.596	1.250	1.791	0.250
	5 min Average	[%]	1.925	1.000	1.084	1.024	1.857	0.862	1.221	0.000
	30 min Average	[%]	0.797	0.355	0.502	0.373	0.791	0.423	0.807	0.000
C1	Maximum	[%]	2.157	0.930	1.461	1.196	1.198	0.664	1.804	2.923
	5 min Average	[%]	1.554	0.490	0.440	0.730	0.367	0.308	1.108	2.001
	30 min Average	[%]	0.673	0.130	0.147	0.248	0.062	0.125	0.895	0.648
C8	Maximum	[%]	1.758	1.131	1.131	1.005	2.197	1.005	1.158	0.503
	5 min Average	[%]	0.073	0.034	0.001	0.002	0.112	0.004	0.012	0.000
	30 min Average	[%]	1.171	0.724	0.664	0.595	1.283	0.589	0.613	0.246

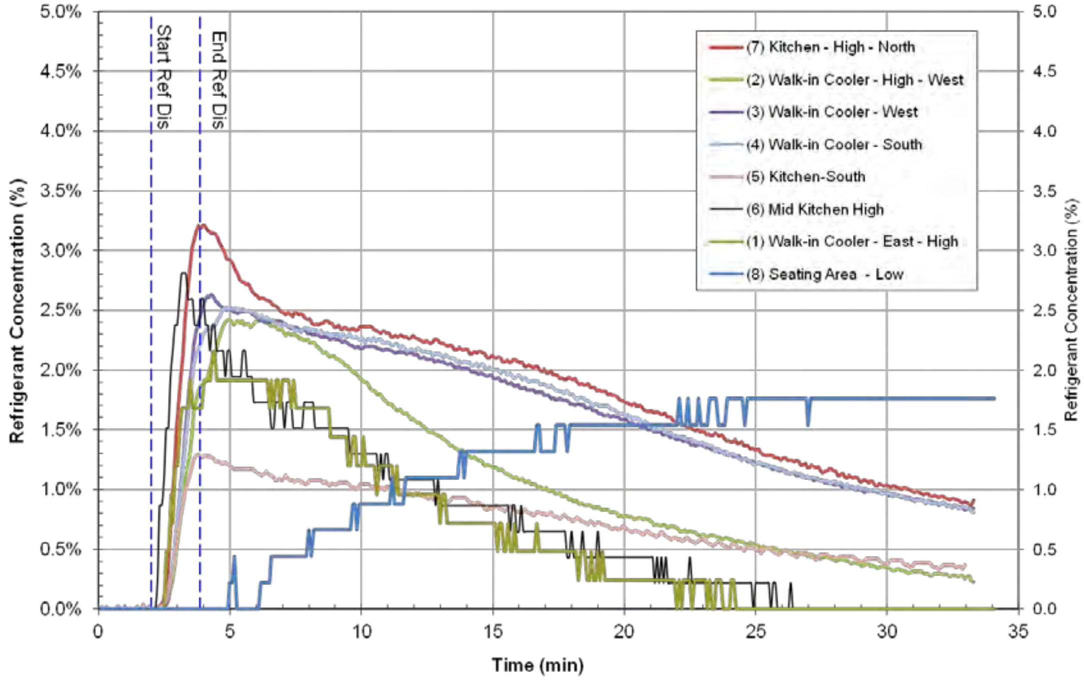


Figure 15 – HFC-32 Concentration Measured during Café Scenario Test with Open Ended Tube (9.5 mm (0.38 in)) [Test 18]

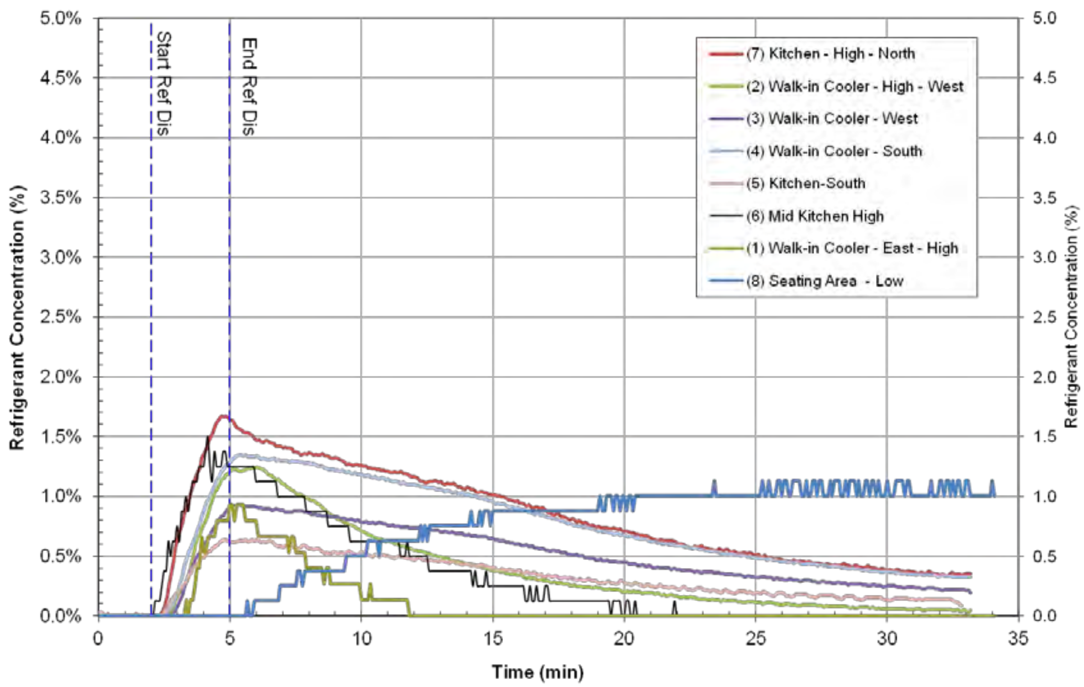


Figure 16 – HFO-1234ze Concentration Measured during Café Scenario Test with Open Ended Tube (9.5 mm (0.38 in)) [Test 14]

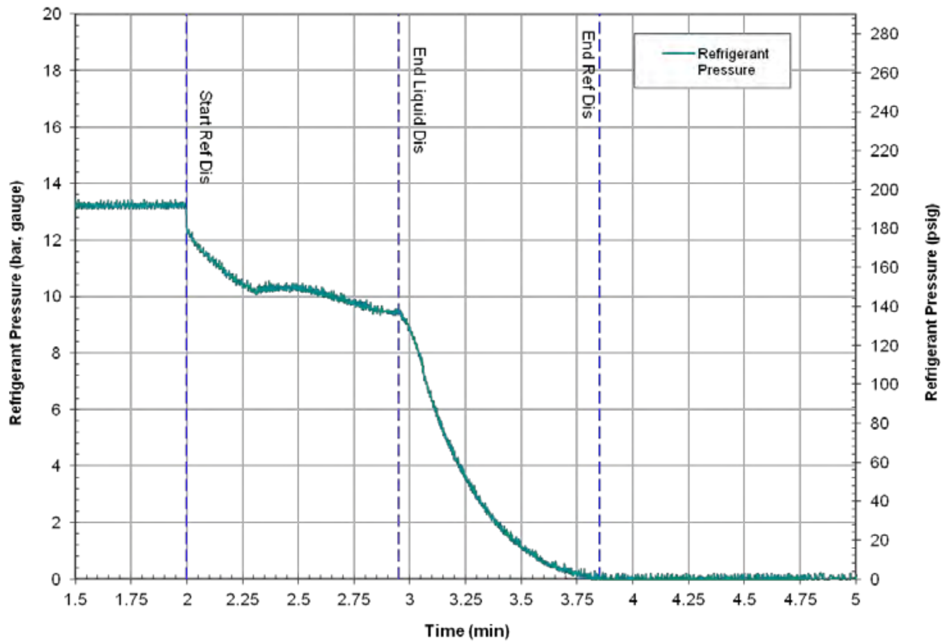


Figure 17 – HFC-32 Cylinder Pressure Measured during Café Scenario Test with Open Ended Tube (9.5 mm (0.38 in)) [Test 18]

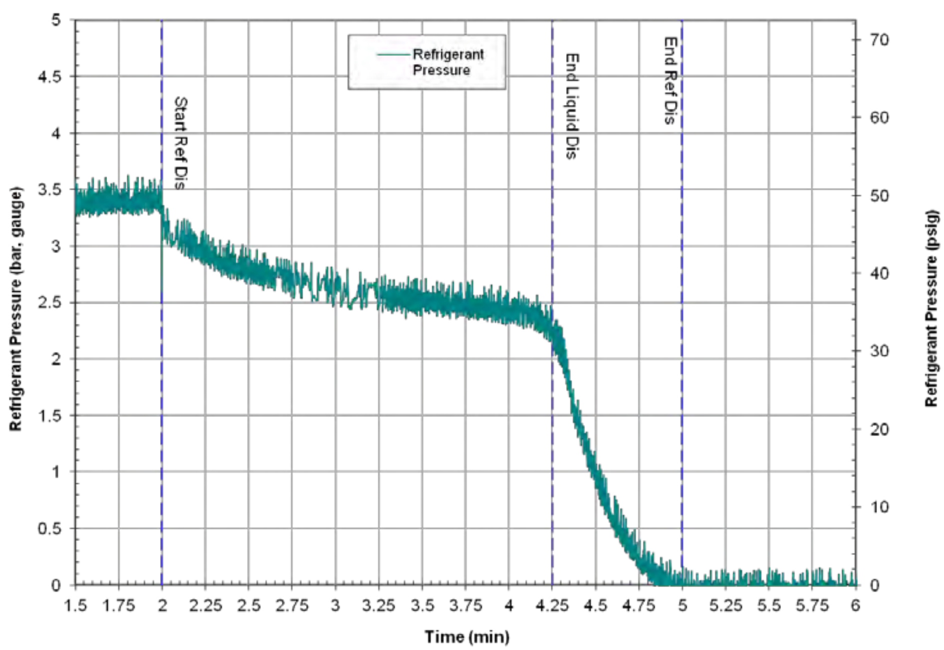


Figure 18 – HFO-1234ze Cylinder Pressure Measured during Café Scenario Test with Open Ended Tube (9.5 mm (0.38 in)) [Test 14]

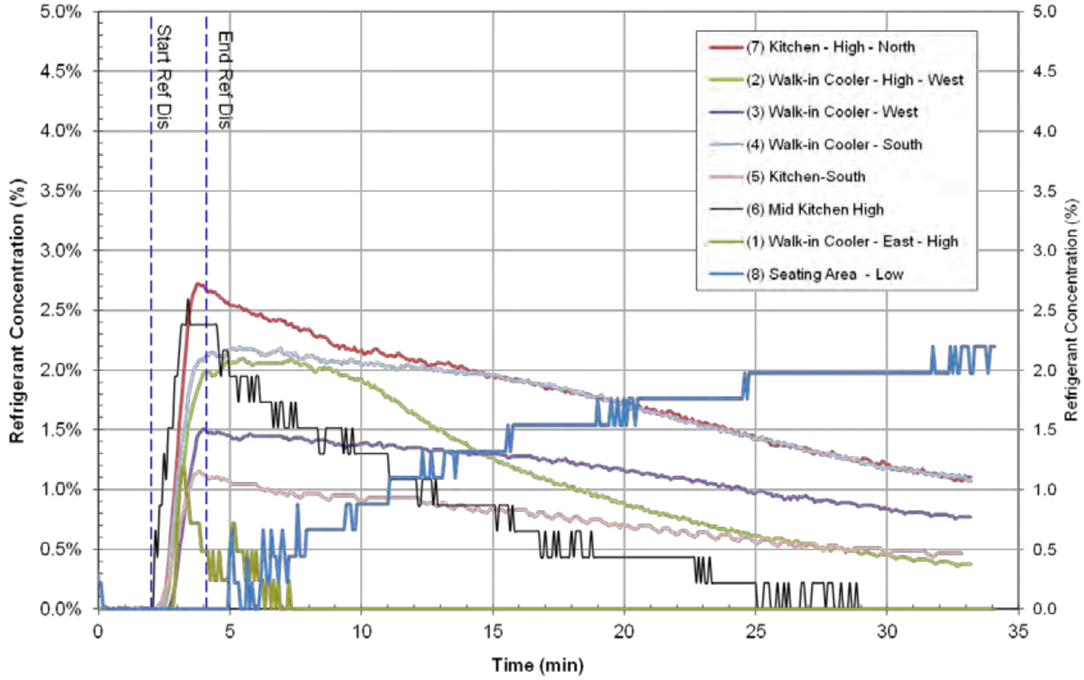


Figure 19 – HFC-32 Concentration Measured during Café Scenario Test with 3.2 mm (0.13 in) orifice [Test 12]

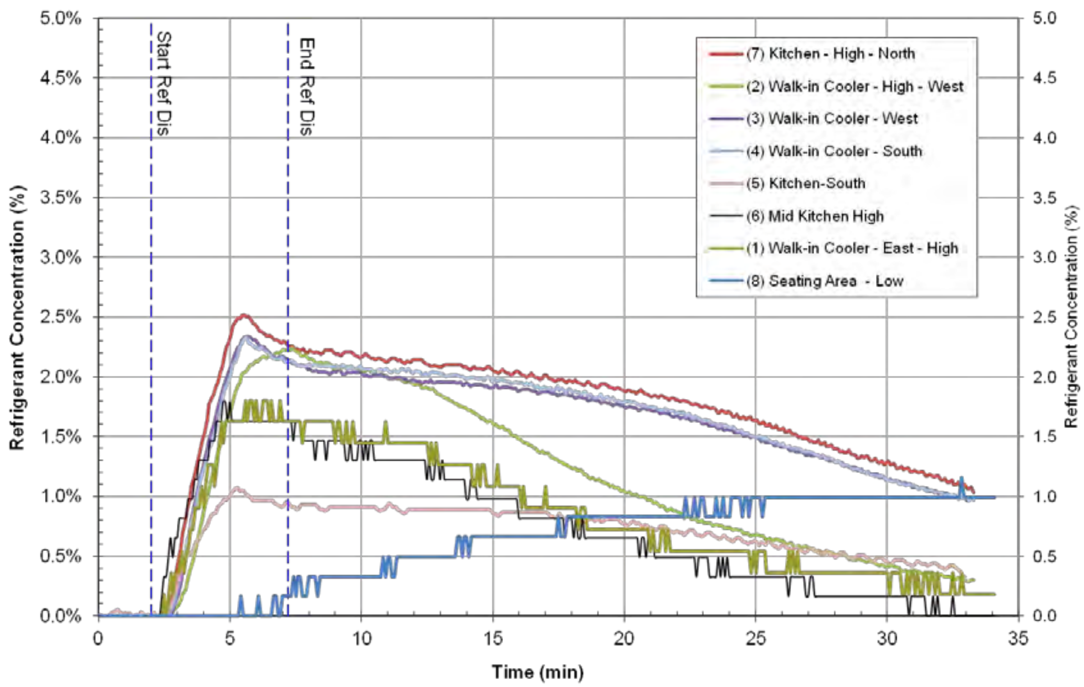


Figure 20 – HFC-32 Concentration Measured during Café Scenario Test with 1.6 mm (0.06 in) orifice [Test 19]

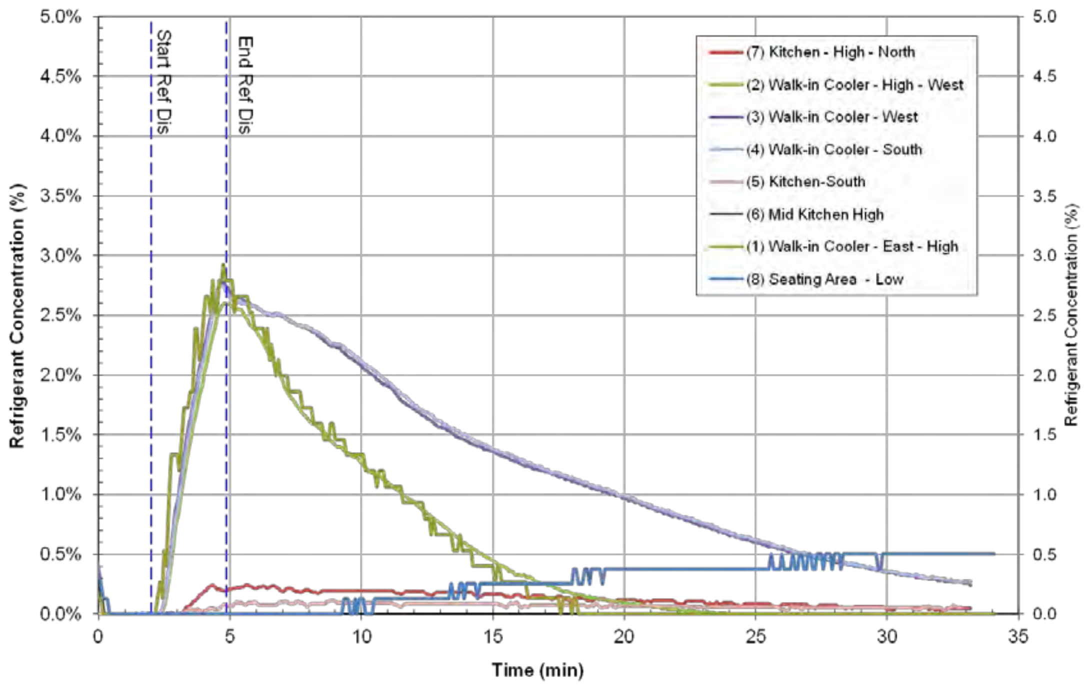


Figure 21 – HFO-1234ze Concentration Measured during Café Scenario Test with Walk-in Cooler Door Closed and Open Ended Tube (9.5 mm (0.38 in)) [Test 17]

During Café scenario testing, the HFO-1234ze, 9.5 mm (0.38 in) test was performed three times, to assess the reproducibility of the testing and the refrigerant concentrations. The results of the reproducibility study are shown in Table 11. In general, the results showed good reproducibility, with the majority of relative standard deviations (RSD) below 10%, and only the RSD of the seating area 5 minute average being greater than 30%.

Table 11 – Reproducibility Results

Sample Location			No Orifice Test 14 HFO-1234ze	Test 15 HFO-1234ze	Test 16 HFO-1234ze	Mean	Standard Deviation	Relative Standard Deviation
C7	Maximum	[%]	1.676	1.569	1.693	1.646	0.055	3.3%
	5 min Average	[%]	1.133	1.065	1.094	1.097	0.028	2.5%
	30 min Average	[%]	0.853	0.810	0.805	0.823	0.022	2.6%
C2	Maximum	[%]	1.242	1.197	1.243	1.228	0.021	1.7%
	5 min Average	[%]	0.766	0.708	0.701	0.725	0.029	4.0%
	30 min Average	[%]	0.400	0.400	0.350	0.383	0.024	6.2%
C3	Maximum	[%]	0.933	1.265	1.379	1.192	0.189	15.9%
	5 min Average	[%]	0.636	0.907	0.943	0.829	0.137	16.5%
	30 min Average	[%]	0.523	0.740	0.733	0.666	0.101	15.1%
C4	Maximum	[%]	1.348	1.232	1.369	1.316	0.060	4.6%
	5 min Average	[%]	0.852	0.770	0.800	0.807	0.034	4.2%
	30 min Average	[%]	0.772	0.729	0.729	0.743	0.020	2.7%
C5	Maximum	[%]	0.638	0.584	0.656	0.626	0.030	4.8%
	5 min Average	[%]	0.442	0.393	0.422	0.419	0.020	4.7%
	30 min Average	[%]	0.339	0.318	0.347	0.335	0.012	3.6%
C6	Maximum	[%]	1.500	1.500	1.500	1.500	0.000	0.0%
	5 min Average	[%]	1.000	1.084	1.024	1.036	0.035	3.4%
	30 min Average	[%]	0.355	0.502	0.373	0.410	0.065	15.9%
C1	Maximum	[%]	0.930	1.461	1.196	1.196	0.217	18.1%
	5 min Average	[%]	0.490	0.440	0.730	0.553	0.126	22.9%
	30 min Average	[%]	0.130	0.147	0.248	0.175	0.052	29.8%
C8	Maximum	[%]	1.131	1.131	1.005	1.089	0.059	5.4%
	5 min Average	[%]	0.034	0.001	0.002	0.012	0.015	123.3%
	30 min Average	[%]	0.724	0.664	0.595	0.661	0.053	8.0%

4.2.2. Luncheon Counter Scenario

A total of five tests were performed in the Luncheon Counter scenario. The refrigerant and cylinder discharge information is shown in Table 12. Test 7 was performed with extra mass (2.5 kg (5 lb)) of refrigerant in the cylinder. Additionally, during Test 7, the analyzer for location C7 was not functioning properly and the data for that location is not reported.

The refrigerant concentration results of the tests are presented in Table 13. The 5 and 30 minute averages are calculated from the time of discharge. In general, for the 0.9 kg (2 lb) tests, the concentrations were less than 0.5% for HFC-32, and less than 0.25% for HFO-1234ze. As seen in the Café tests, HFC-32 discharge creates higher refrigerant concentrations in the space than HFO-1234ze as illustrated in Figures 22 and 23. Typically, locations C4 (in the center of the room in the direction of discharge) and C8 (0.3 m from the floor) were measured as having the highest concentrations. The 2.3 kg (5 lb) test produced concentrations approximately double the 0.9 kg (2 lb) test. For all tests, location C1 did not detect any refrigerant. This is likely due to the detection limitations of the analyzers and the generally low concentrations in the space.

Table 12 – Luncheon Counter Scenario Refrigerant Discharge Description

Test ID	Refrigerant	Orifice Size (mm)	Refrigerant Mass		Refrigerant Discharge Time		Avg. Discharge Rate (Liquid 80%)		Avg. Discharge Rate (Total)	
			kg	lb	Liquid (s)	Total (s)	kg/s	lb/s	kg/s	lb/s
7	HFC-32	9.5	2.3	5.0	21.0	81.0	0.086	0.190	0.028	0.062
8	HFC-32	9.5	0.9	2.0	6.0	60.0	0.121	0.267	0.015	0.033
9	HFO-1234ze	9.5	0.9	2.0	18.0	66.0	0.040	0.089	0.014	0.030
11	HFC-32	3.2	0.9	2.0	12.0	75.0	0.060	0.133	0.012	0.027
10	HFO-1234ze	3.2	0.9	2.0	24.0	78.0	0.030	0.067	0.012	0.026

Table 13 – Luncheon Counter Scenario Test Concentration Results

Sample Location			Extra Mass	9.5 mm (3/8in) Orifice		3 mm (1/8 in) Orifice	
			Test 7	Test 8	Test 9	Test 11	Test 10
			HFC-32	HFC-32	HFO-1234ze	HFC-32	HFO-1234ze
C7	Maximum	[%]	-	0.466	0.204	0.329	0.162
	5 min Average	[%]	-	0.231	0.127	0.231	0.097
	30 min Average	[%]	-	0.332	0.158	0.266	0.134
C2	Maximum	[%]	0.811	0.392	0.103	0.374	0.157
	5 min Average	[%]	0.597	0.225	0.051	0.234	0.093
	30 min Average	[%]	0.609	0.243	0.051	0.228	0.098
C3	Maximum	[%]	0.424	0.230	0.098	0.189	0.094
	5 min Average	[%]	0.313	0.140	0.054	0.127	0.060
	30 min Average	[%]	0.372	0.192	0.057	0.138	0.077
C4	Maximum	[%]	1.204	0.594	0.239	0.440	0.339
	5 min Average	[%]	0.653	0.255	0.088	0.291	0.154
	30 min Average	[%]	0.633	0.233	0.058	0.276	0.146
C5	Maximum	[%]	0.338	0.159	0.077	0.174	0.085
	5 min Average	[%]	0.263	0.091	0.026	0.114	0.052
	30 min Average	[%]	0.246	0.094	0.020	0.099	0.055
C6	Maximum	[%]	0.649	0.433	0.250	0.433	0.125
	5 min Average	[%]	0.415	0.139	0.077	0.164	0.090
	30 min Average	[%]	0.420	0.075	0.039	0.173	0.044
C1	Maximum	[%]	0.000	0.000	0.000	0.000	0.000
	5 min Average	[%]	0.000	0.000	0.000	0.000	0.000
	30 min Average	[%]	0.000	0.000	0.000	0.000	0.000
C8	Maximum	[%]	0.659	1.099	0.377	0.879	0.377
	5 min Average	[%]	0.203	0.207	0.212	0.104	0.112
	30 min Average	[%]	0.394	0.350	0.241	0.199	0.123

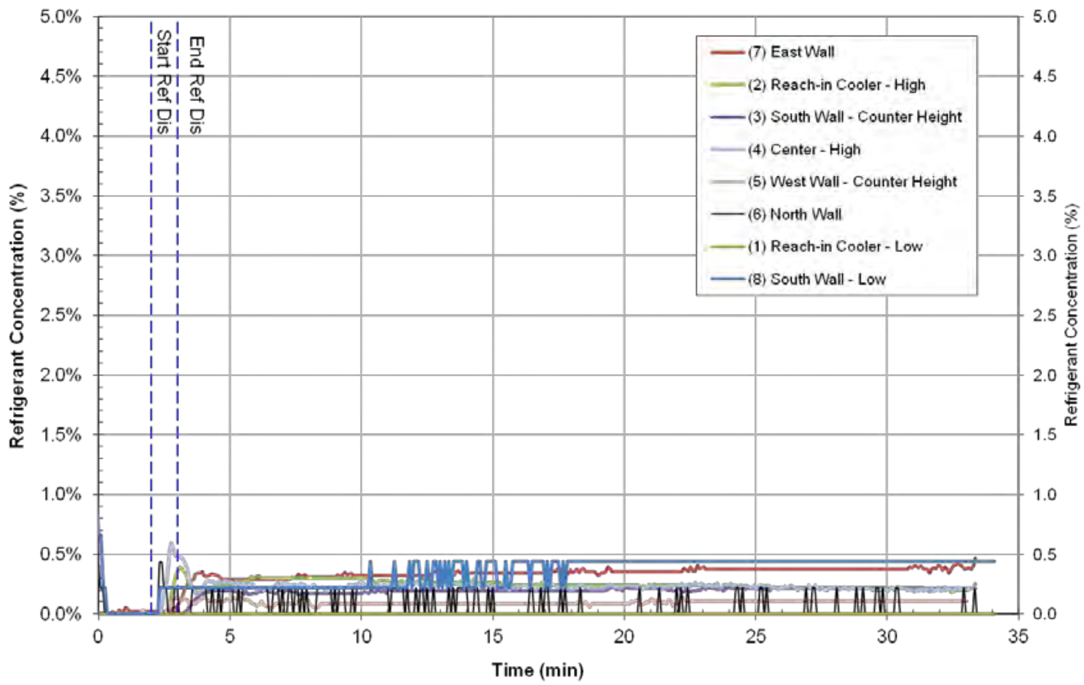


Figure 22 – HFC-32 Concentrations Measured during Luncheon Counter Scenario tests with Open Ended Tube (9.5 mm (0.38 in)) [Test 8]

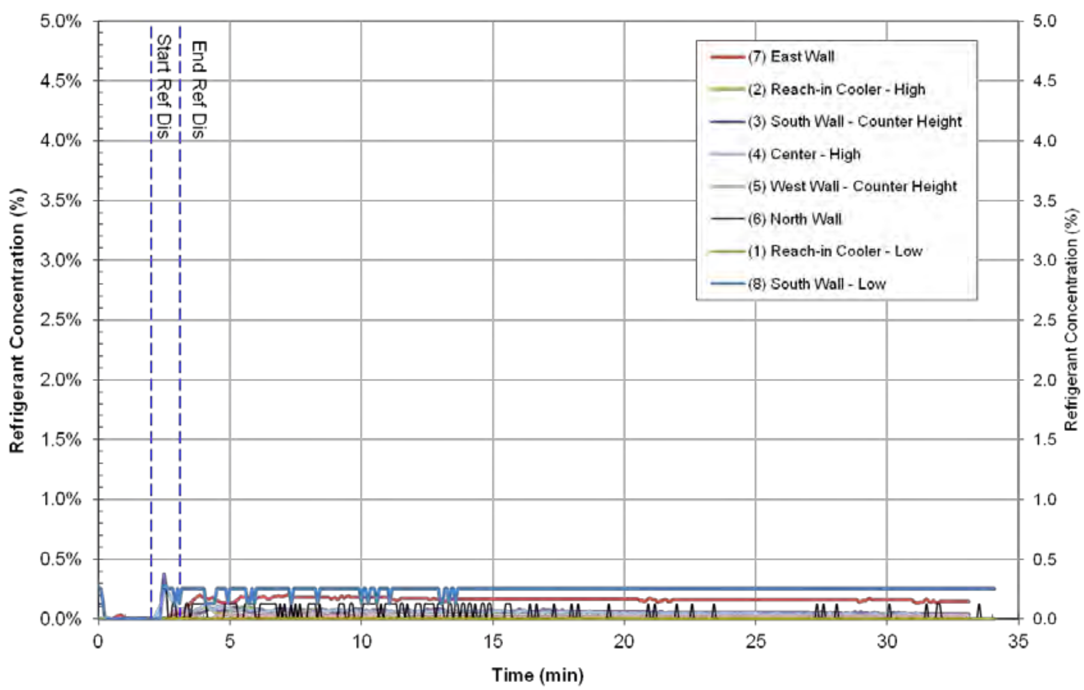


Figure 23 – HFO-1234ze Concentrations Measured during Luncheon Counter Scenario tests with Open Ended Tube (9.5 mm (0.38 in)) [Test 9]

4.2.3. Convenience Store Scenario

A total of two tests were performed in the Convenience Store scenario. The refrigerant and cylinder discharge information is shown in Table 14. As seen in other tests, the HFC-32, due to its higher cylinder pressure (approximately 200 psi) discharges faster than the HFO-1234ze (approximate cylinder pressure of 50 psi). The concentration results are presented in Table 15. The 5 and 30 minute averages are calculated from the time of discharge. In general, the concentrations were less than 1% for HFC-32 and less than 0.5% for HFO-1234ze as illustrated in Figures 24 and 25.

Table 14 – Convenience Store Scenario Refrigerant Discharge Description

Test ID	Refrigerant	Orifice Size (mm)	Refrigerant Mass		Refrigerant Discharge Time		Avg. Discharge Rate (Liquid 80%)		Avg. Discharge Rate (Total)	
			kg	lb	Liquid (s)	Total (s)	kg/s	lb/s	kg/s	lb/s
20	HFC-32	9.5	2.3	5.0	22.2	78.0	0.082	0.180	0.029	0.064
21	HFO-1234ze	9.5	2.3	5.0	63.0	105.0	0.029	0.063	0.022	0.048

Table 15 – Convenience Store Scenario Test Concentration Results

Sample Location			Test 20	Test 21
			HFC-32	HFO-1234ze
C7	Maximum	[%]	0.447	0.104
	5 min Average	[%]	0.231	0.044
	30 min Average	[%]	0.351	0.056
C2	Maximum	[%]	0.681	0.082
	5 min Average	[%]	0.460	0.031
	30 min Average	[%]	0.501	0.018
C3	Maximum	[%]	0.494	0.499
	5 min Average	[%]	0.387	0.359
	30 min Average	[%]	0.434	0.405
C4	Maximum	[%]	0.705	0.140
	5 min Average	[%]	0.489	0.069
	30 min Average	[%]	0.482	0.055
C5	Maximum	[%]	0.450	0.417
	5 min Average	[%]	0.243	0.215
	30 min Average	[%]	0.210	0.181
C6	Maximum	[%]	0.649	0.500
	5 min Average	[%]	0.544	0.309
	30 min Average	[%]	0.454	0.327
C1	Maximum	[%]	0.000	0.664
	5 min Average	[%]	0.000	0.319
	30 min Average	[%]	0.000	0.230
C8	Maximum	[%]	1.099	0.251
	5 min Average	[%]	0.392	0.025
	30 min Average	[%]	0.694	0.006

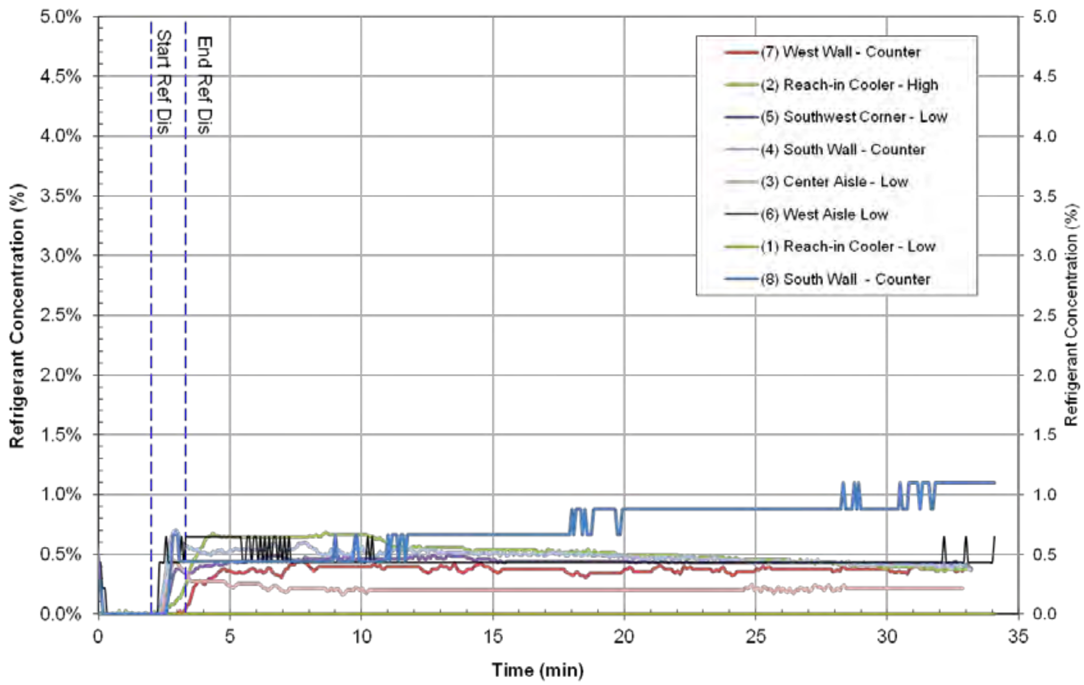


Figure 24 – HFC-32 Concentrations Measured during Convenience Store Scenario with Open Ended Tube (9.5 mm (0.38 in)) [Test 20]

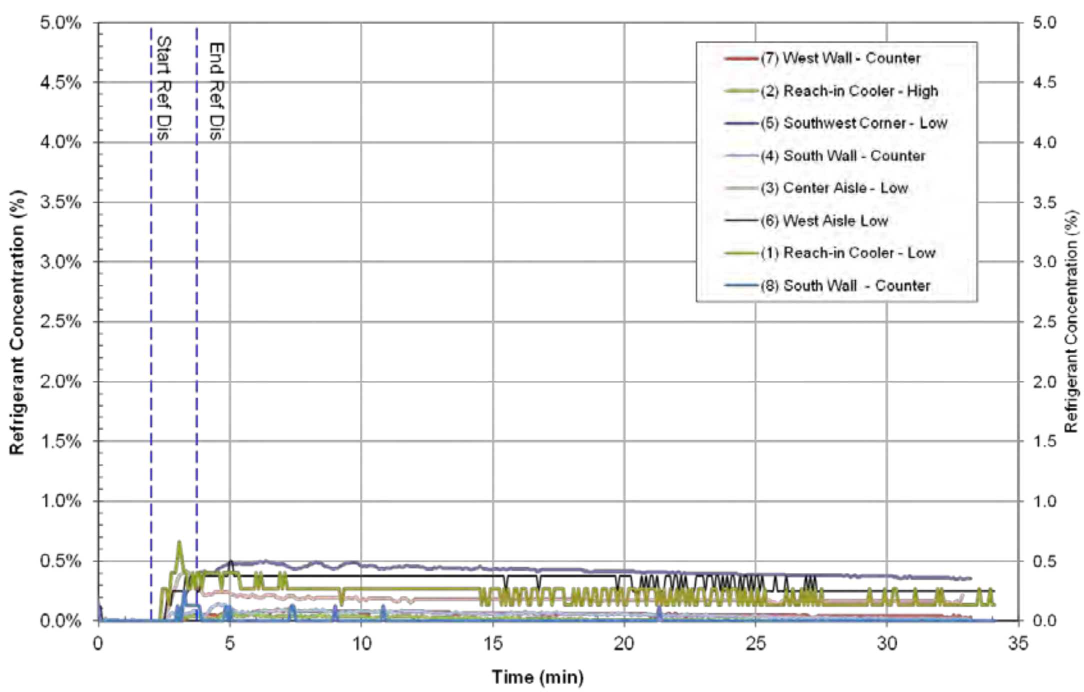


Figure 25 – HFO-1234ze Concentrations Measured during Convenience Store Scenario with Open Ended Tube (9.5 mm (0.38 in)) [Test 21]

5. CONCLUSIONS

During testing, no refrigerant concentrations were observed within the flammable ranges of the respective refrigerants. For HFC-32 discharges, the concentrations observed were less than 3.3% for all Café scenario discharges, less than 1.1% for all Luncheon Counter scenario discharges, and less than 1.1 % for all Convenience Store scenario discharges. Per the MSDS, the LEL for HFC-32 is 14% per volume air. HFO-1234ze is listed as non-flammable below 30°C (86°F), and concentrations did not exceed 1.8% in the Café scenario, 0.4% in the Luncheon Counter scenario, and 0.7 % in the Convenience Store scenario.

In general, HFC-32 had a higher vapor pressure, more rapid discharge time, and produced greater concentrations than HFO-1234ze.

6. REFERENCES

1. "Thermodynamic Properties of DuPont™ Freon® 22," Technical Information Bulletin AT-22, E.I. du Pont de Nemours & Co., Inc., Wilmington, DE, August, 2004.
2. “DuPont™ Suva® 407C (R-407C) and DuPont™ Suva® 410A (R-410A) Properties, Use, Storage and Handling," Technical Information Bulletin P407C/410A, E.I. du Pont de Nemours & Co., Inc., Wilmington, DE, June, 2003.
3. Bowman, James M. and Williams, David J., "HBA-1 Blowing Agent Commercialization Status," Honeywell International, Inc., Morristown, NJ, 2008.
4. Honeywell, "Honeywell HFO-1234ze Blowing Agent," Honeywell International, Inc., Morristown, NJ, 2008.
5. Higashi, Yukihiro, "Thermophysical Properties of HFO-1234yf and HFO-1234ze(E)," 2010 International Symposium on Next-generation Air Conditioning and Refrigeration Technology, Tokyo, Japan, February, 17-19, 2010.
6. "DuPont™ Formacel® Z-2 Foam Expansion Agent," Technical Information Bulletin, E.I. du Pont de Nemours & Co., Inc., Wilmington, DE, August, 2002.
7. “DuPont™ FE-25® Fire Extinguishing Agent," Technical Information Bulletin, E.I. du Pont de Nemours & Co., Inc., Wilmington, DE, November, 2006.
8. DuPont, “Material Safety Data Sheet: HFC-32," MSDS 6300FR, E.I. du Pont de Nemours & Co., Inc., Wilmington, DE, May 15, 2007.
9. Honeywell, “Safety Data Sheet: HFO-1234ze, HBA-1,” Honeywell International, Inc., Morristown, NJ, August 13, 2008.

APPENDIX A. INDIVIDUAL TEST RESULTS

A.1. Café Test Results

A.1.1. Test 18 – HFC-32, 9.5 mm (0.38 in) Orifice

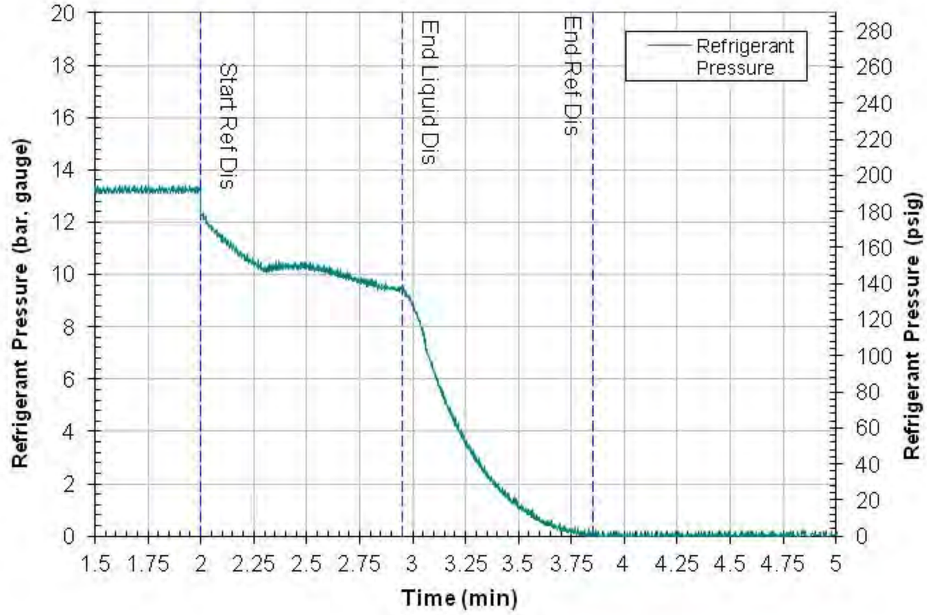


Figure A-1 – Test 18 Refrigerant Cylinder Pressure

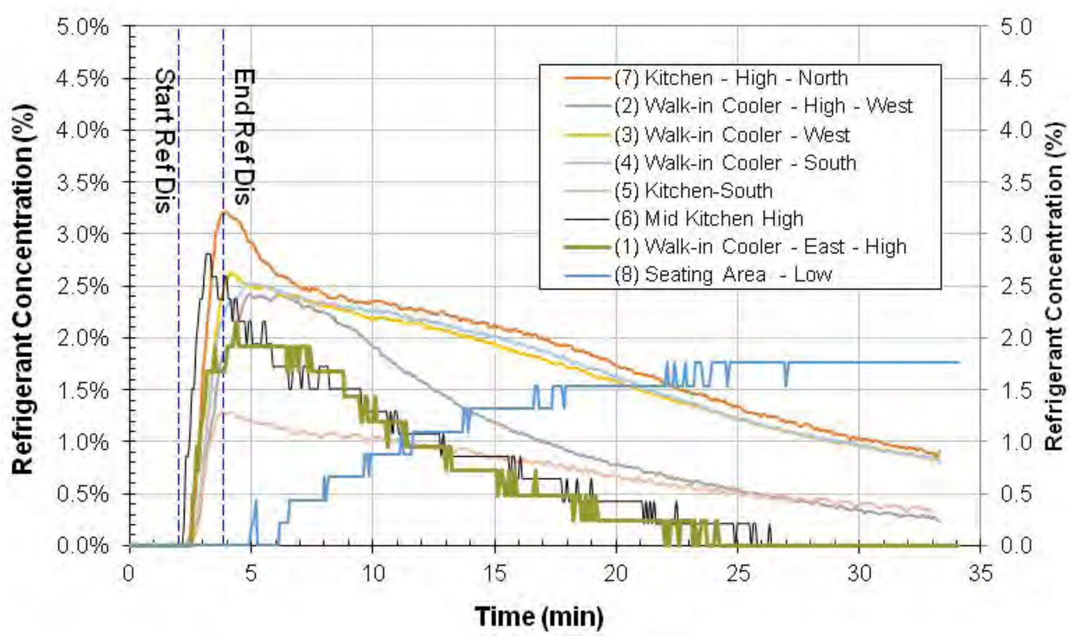


Figure A-2 – Test 18 HFC-32 Concentrations

A.1.2. Test 14 – HFO-1234ze, 9.5 mm (0.38 in) Orifice

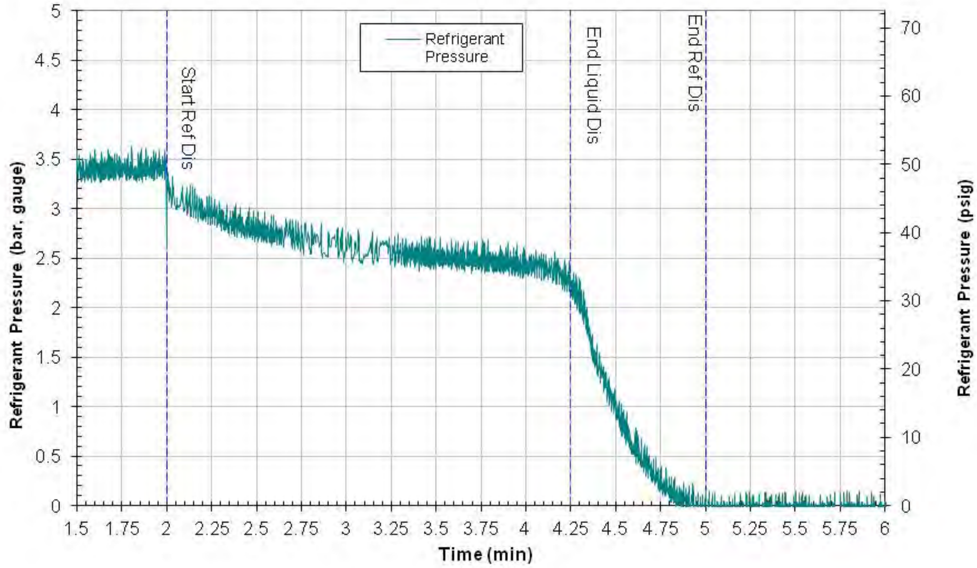


Figure A-3 – Test 14 Refrigerant Cylinder Pressure

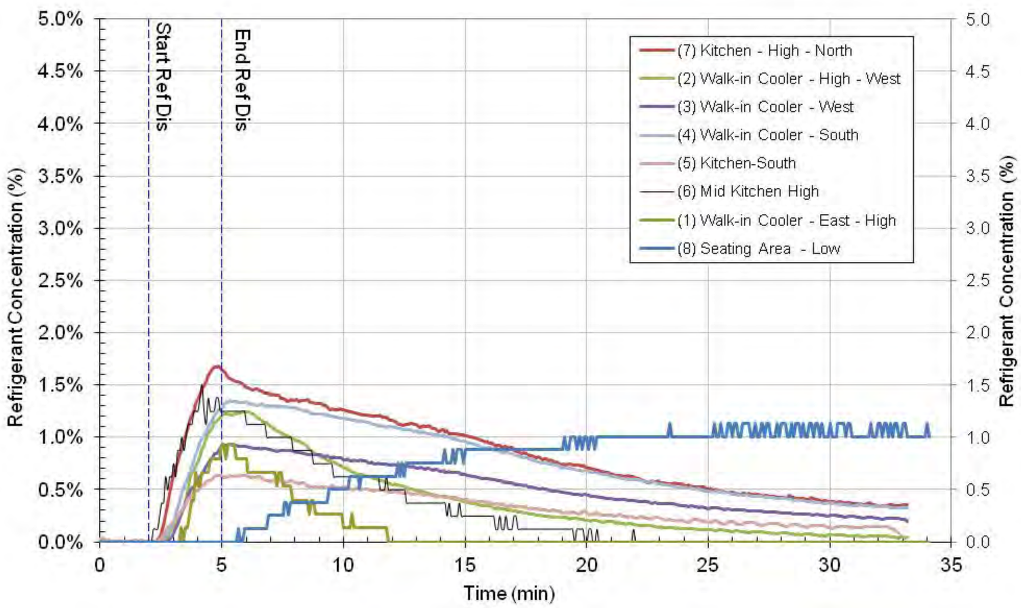


Figure A-4 – Test 14 HFO-1234ze Concentrations

A.1.3. Test 12 – HFC-32, 3.2 mm (0.13 in) Orifice

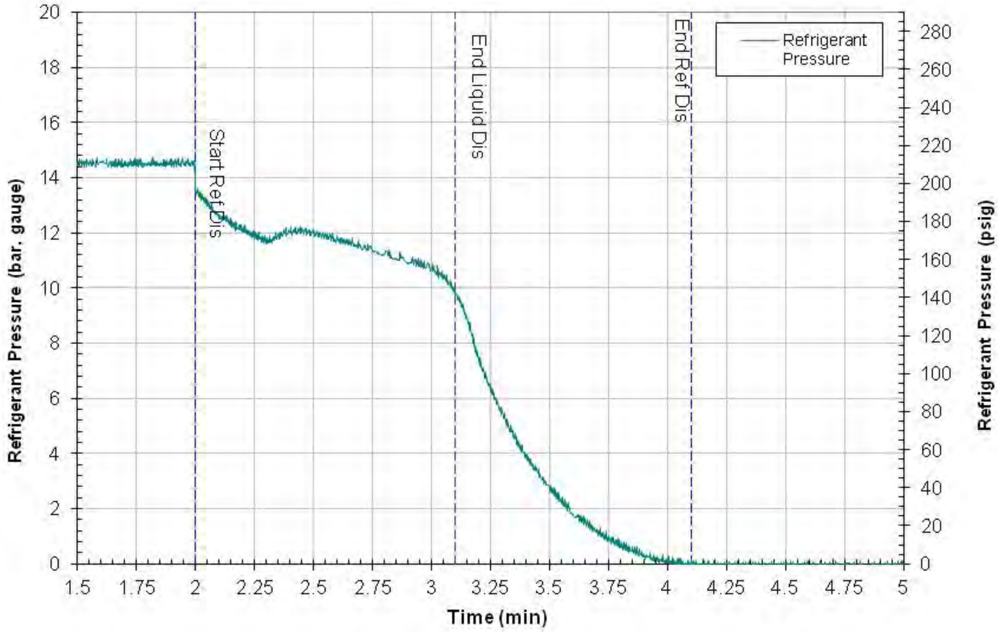


Figure A-5 – Test 12 Refrigerant Cylinder Pressure

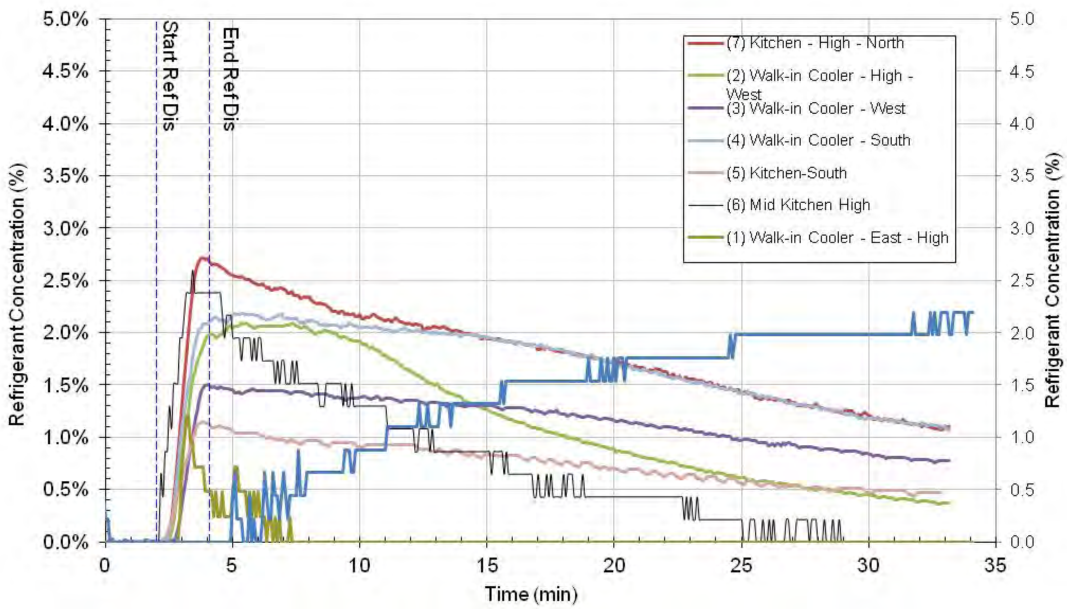


Figure A-6 – Test 12 HFC-32 Concentrations

A.1.4. Test 13 – HFO-1234ze, 3.2 mm (0.13 in) Orifice

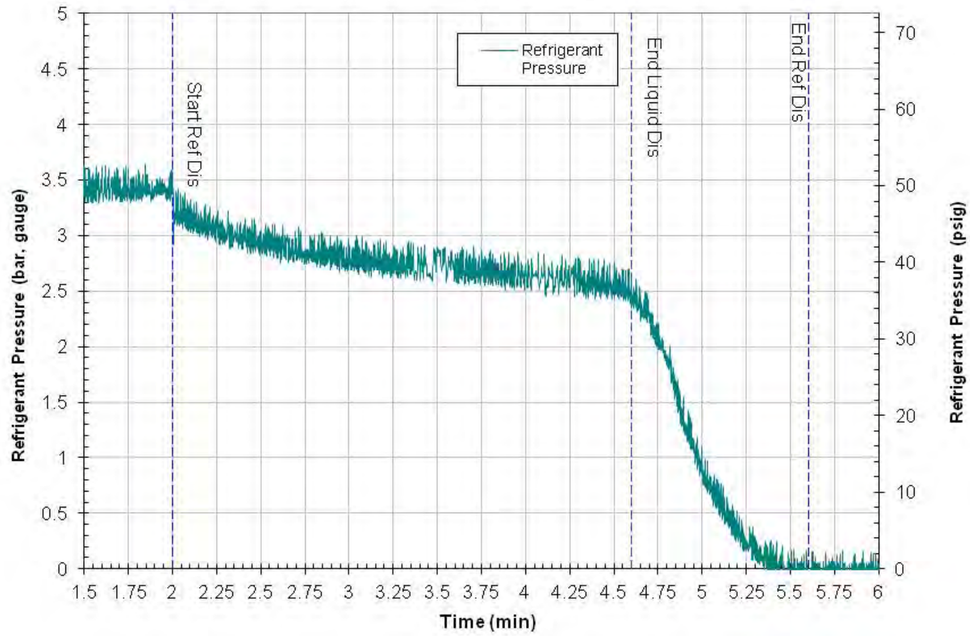


Figure A-7 – Test 13 Refrigerant Cylinder Pressure

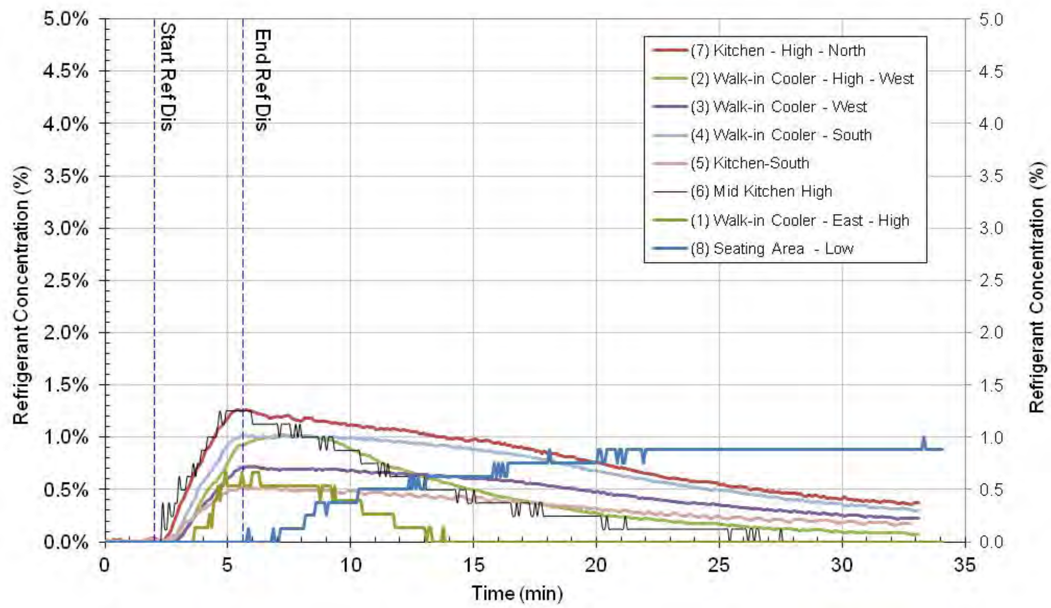


Figure A-8 – Test 13 HFO-1234ze Concetrations

A.1.5. Test 19 – HFC-32, 1.5 mm (0.06 in) Orifice

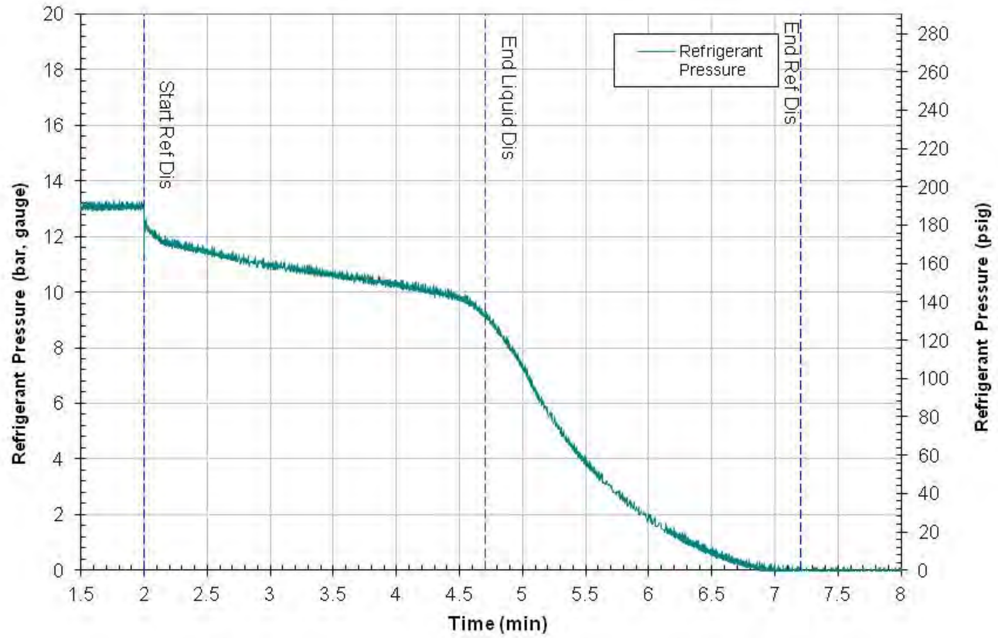


Figure A-9 – Test 19 Refrigerant Cylinder Pressure

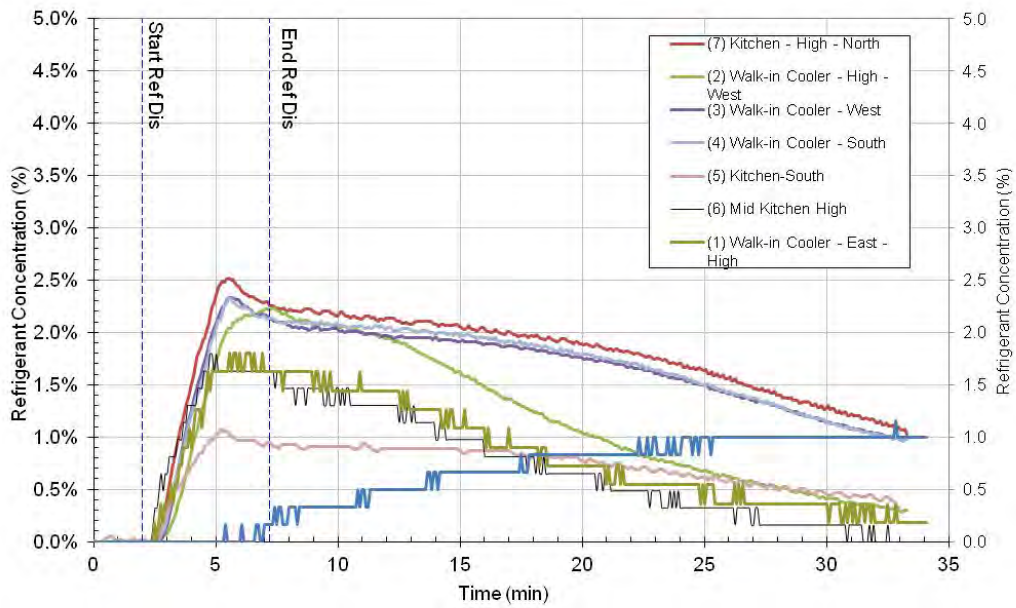


Figure A-10 – Test 19 HFC-32 Concentrations

A.1.6. Test 17 – HFO-1234ze, 9.5 mm (0.38 in) Orifice, Walk-in Freezer Door Closed

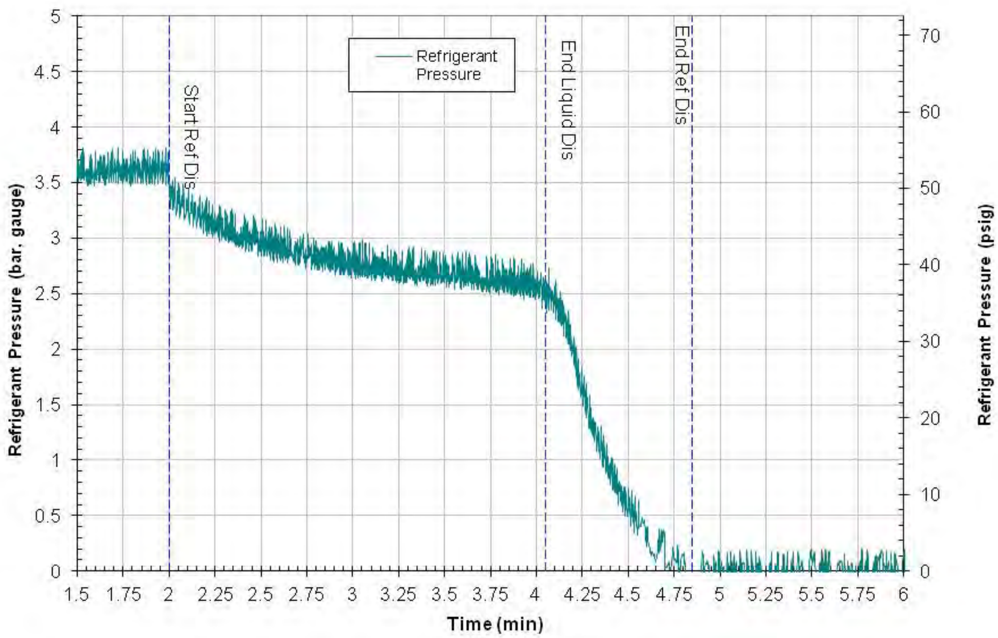


Figure A-11 – Test 17 Refrigerant Cylinder Pressure

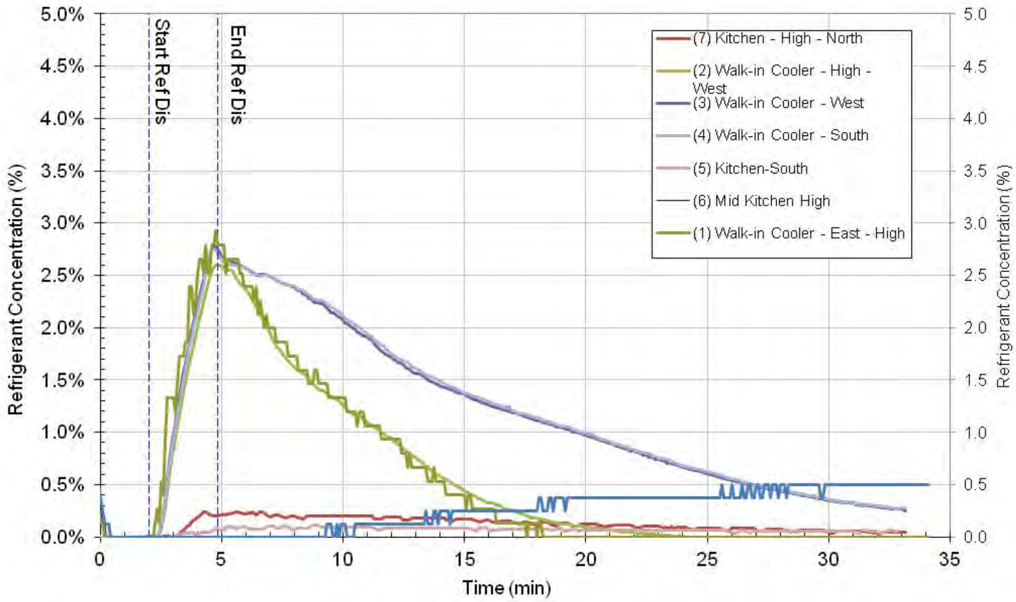


Figure A-12 – Test 17 HFO-1234ze Concentrations

A.2. Luncheon Counter Results

A.2.1. Test 7 – HFC-32, 9.5 mm (0.38 in) Orifice, Extra Mass

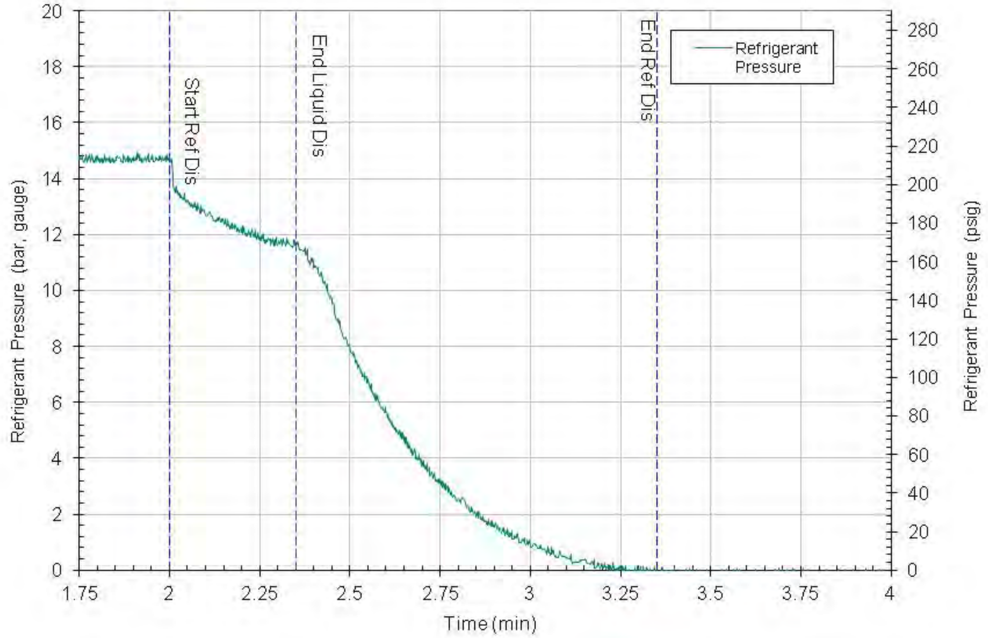


Figure A-13 – Test 7 Refrigerant Cylinder Pressure

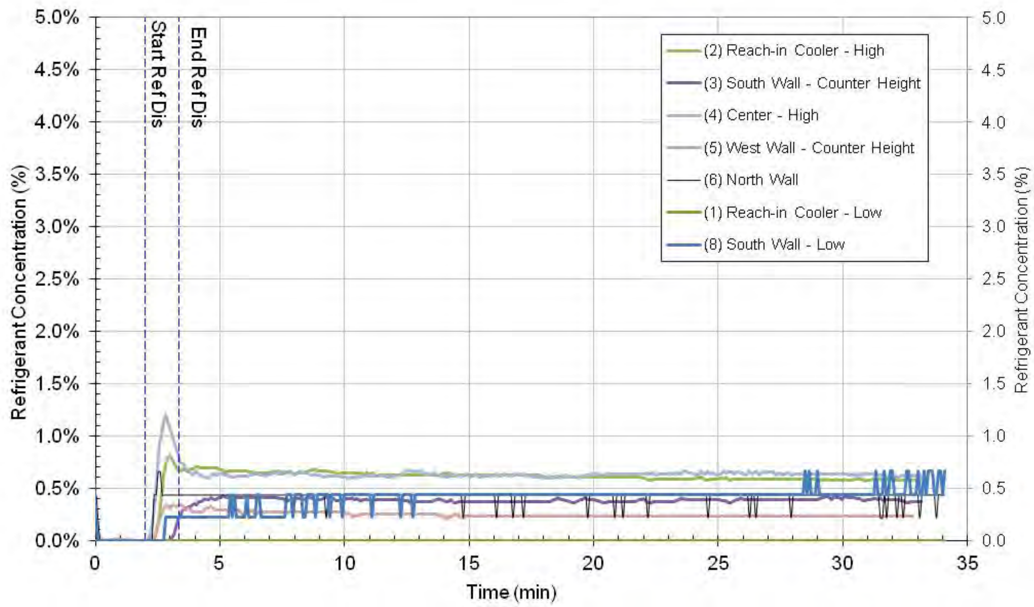


Figure A-14 – Test 7 HFC-32 Concentrations

A.2.2. Test 8 – HFC-32, 9.5 mm (0.38 in) Orifice

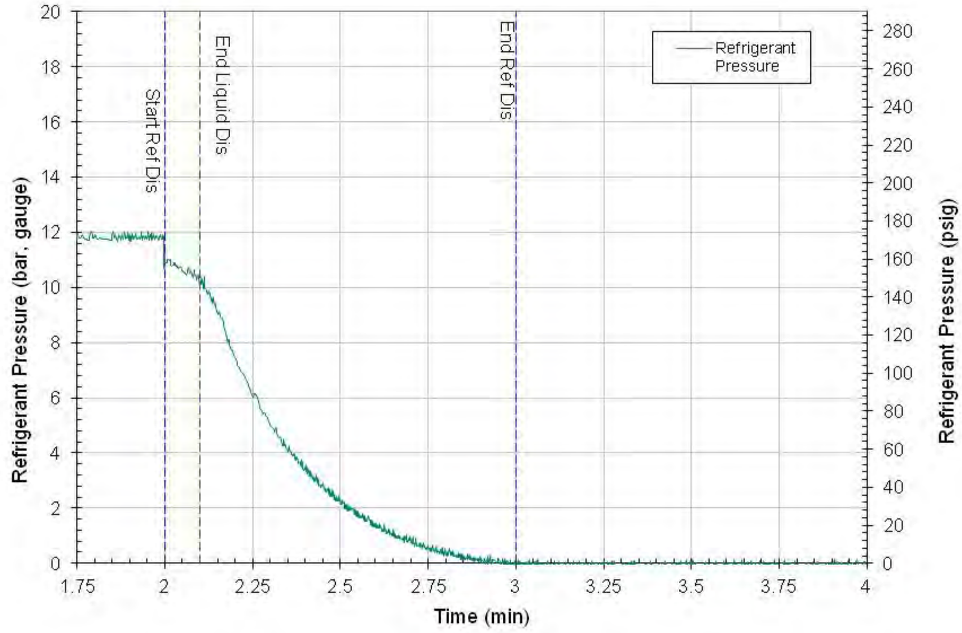


Figure A-15 – Test 8 Refrigerant Cylinder Pressure

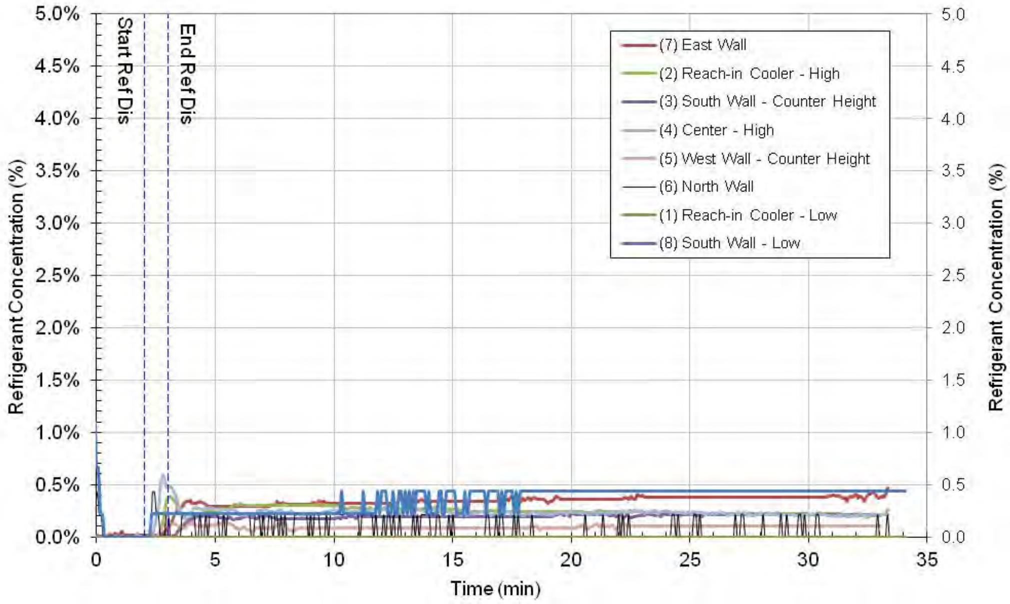


Figure A-16 – Test 8 HFC-32 Concentrations

A.2.3. Test 9 – HFO-1234ze, 9.5 mm (0.38 in) Orifice

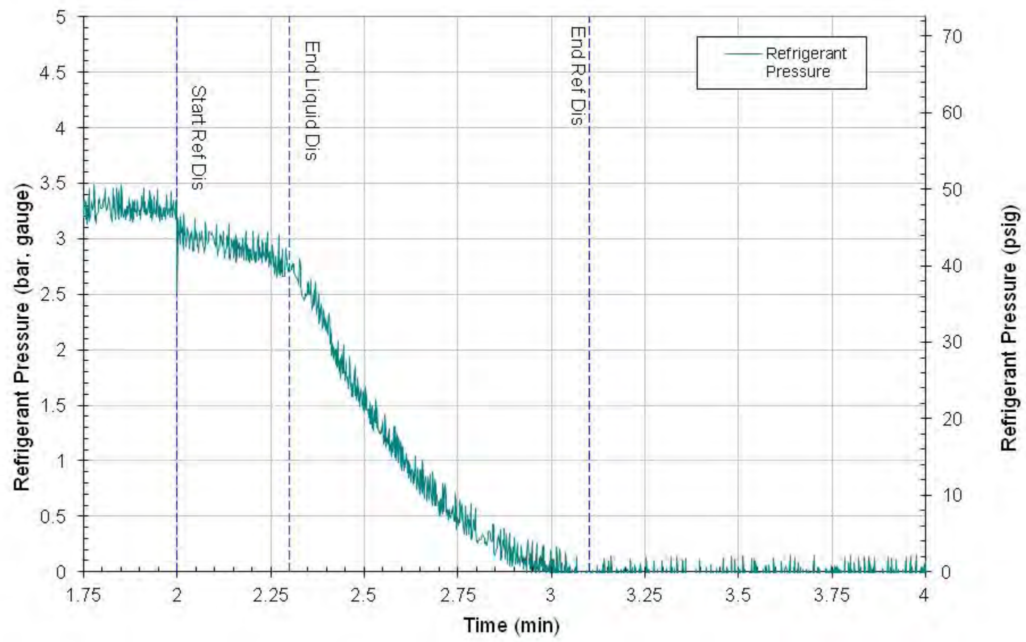


Figure A-17 – Test 9 Refrigerant Cylinder Pressure

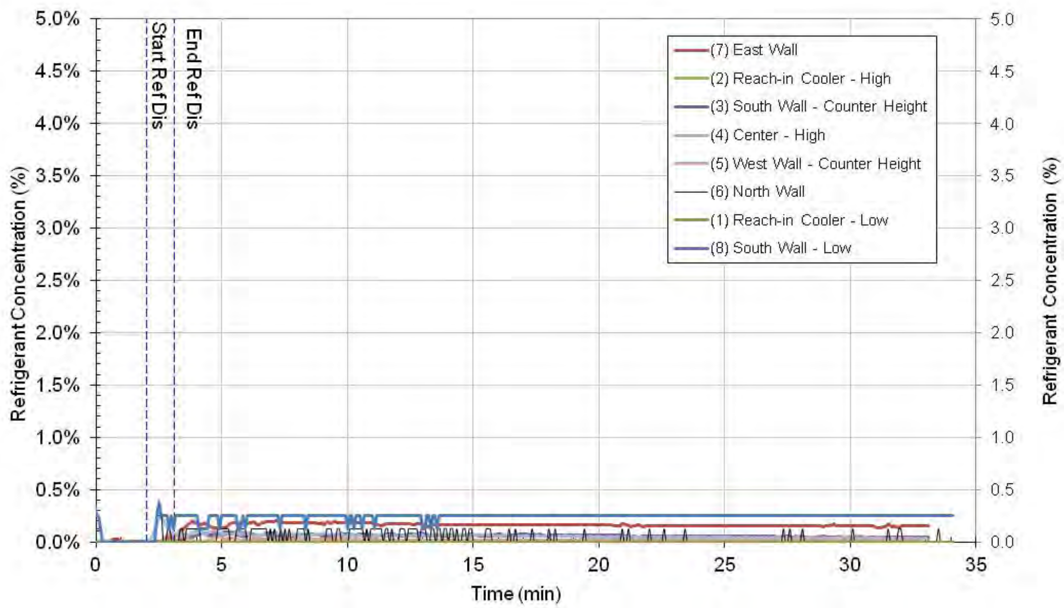


Figure A-18 – Test 9 HFO-1234ze Concentrations

A.2.4. Test 11 – HFC-32, 3mm (0.13 in) Orifice

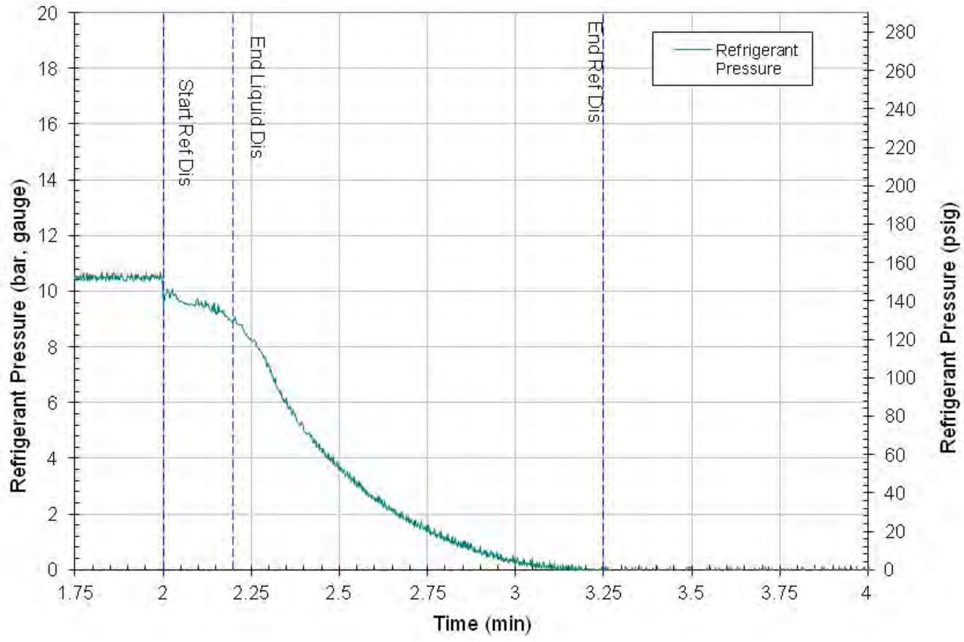


Figure A-19 – Test 11 Refrigerant Cylinder Pressure

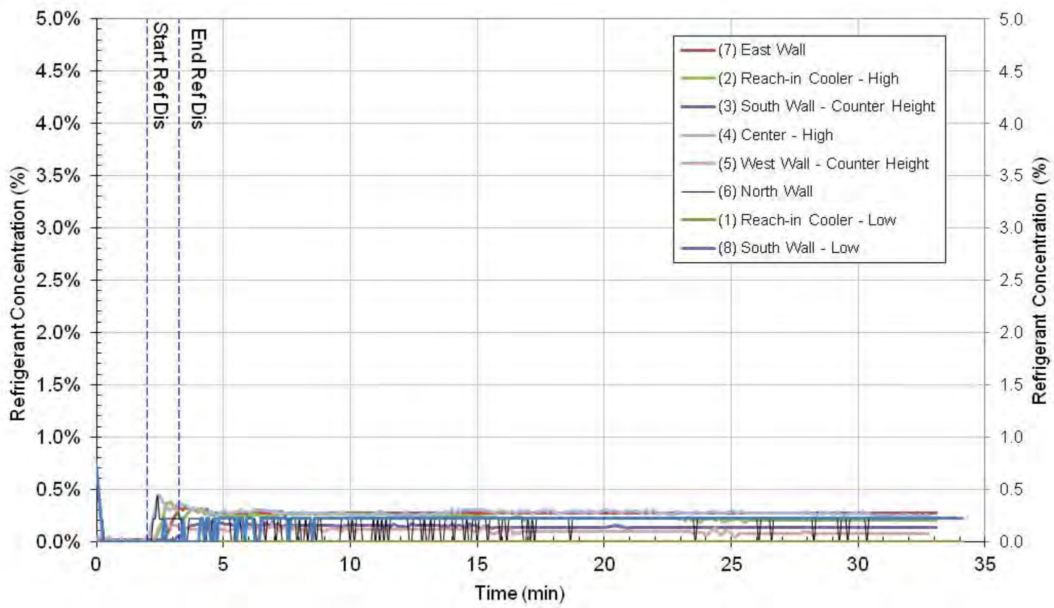


Figure A-20 – Test 11 HFC-32 Concentrations

A.2.5. Test 10 – HFO-1234ze, 3mm (0.13 mm) Orifice

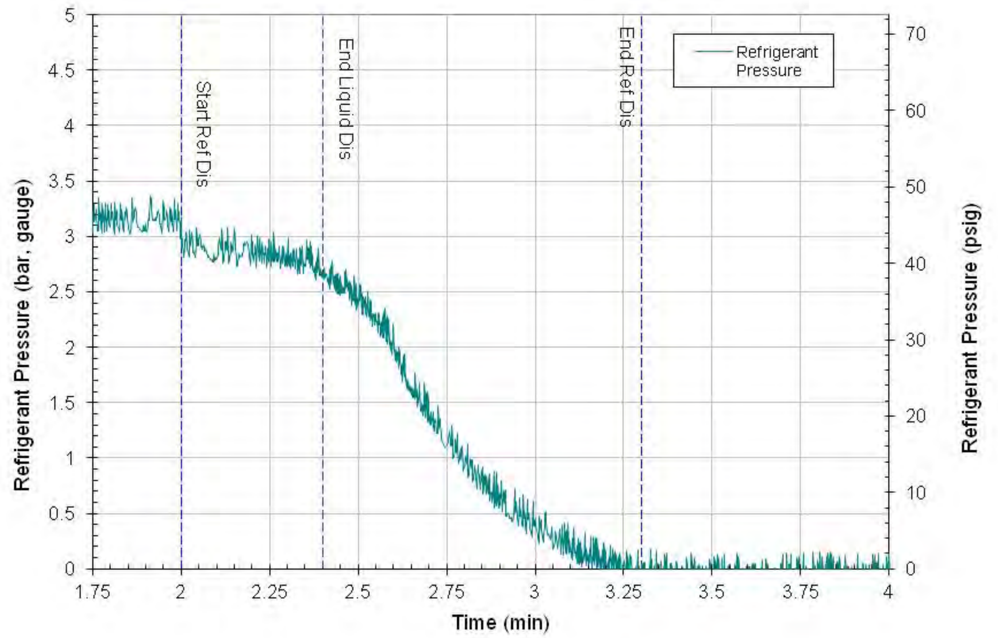


Figure A-21 – Test 10 Refrigerant Cylinder Pressure

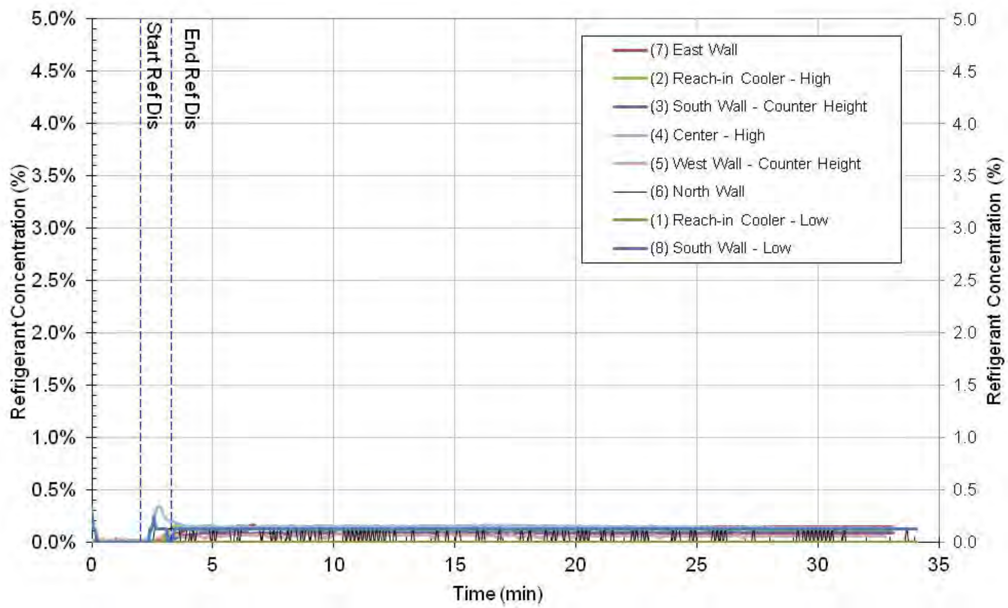


Figure A-22 – Test 10 HFO-1234ze Concentrations

A.3. Convenience Store Results

A.3.1. Test 20 – HFC-32, 9.5 mm (0.38 in) Orifice

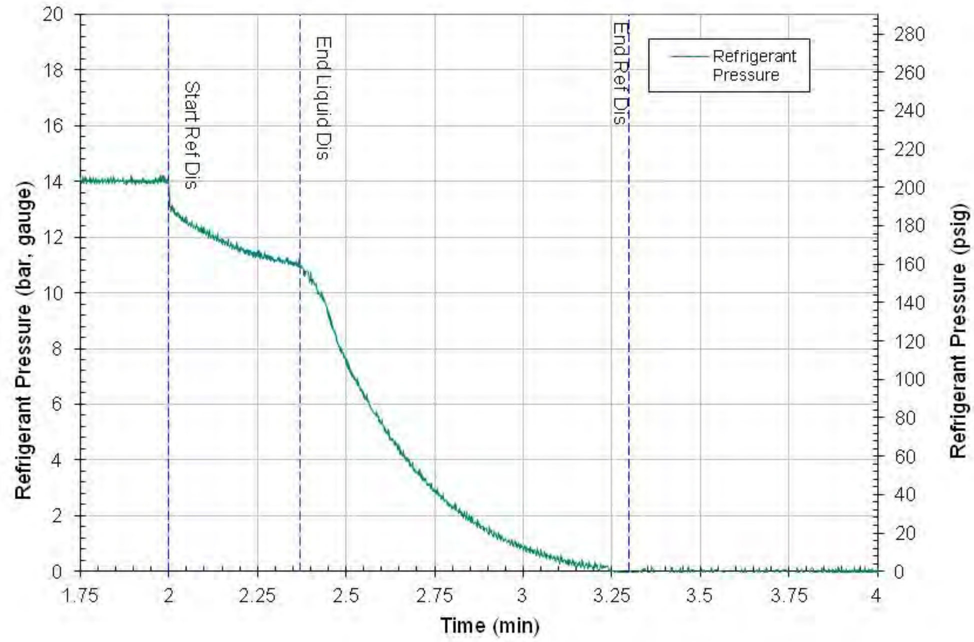


Figure A-23 – Test 20 Refrigerant Cylinder Pressure

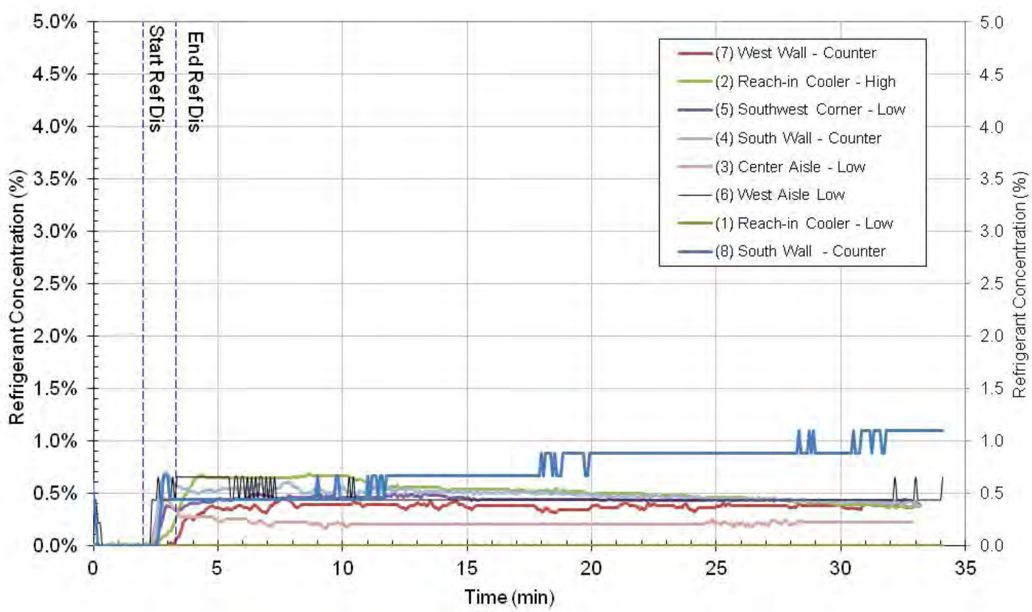


Figure A-24 – Test 20 HFC-32 Concentrations

A.3.2. Test 21 – HFO-1234ze, 9.5 mm (0.38 in) Orifice

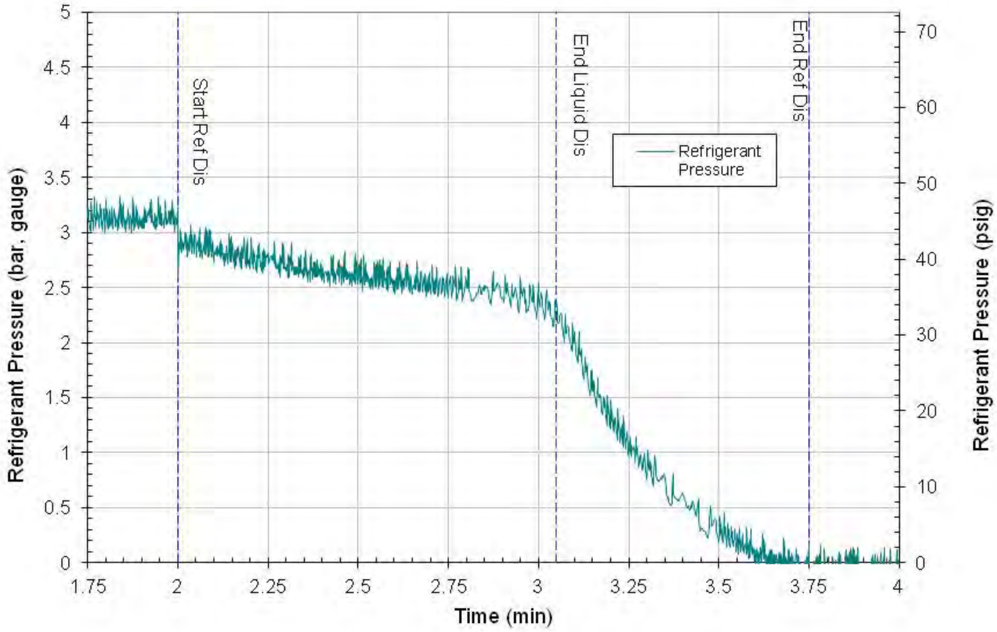


Figure A-25 – Test 21 Refrigerant Cylinder Pressure

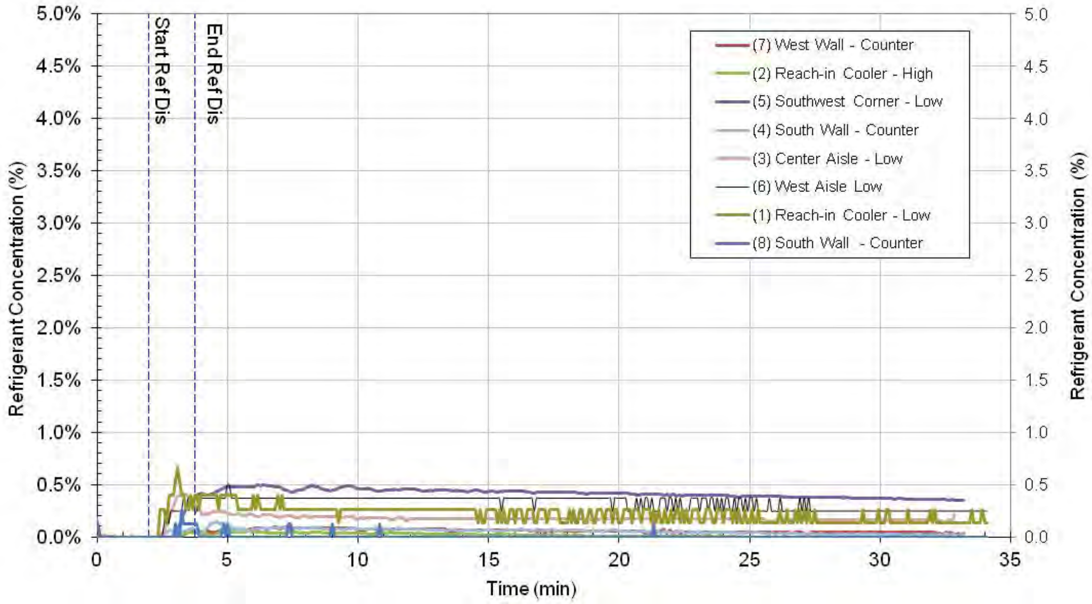
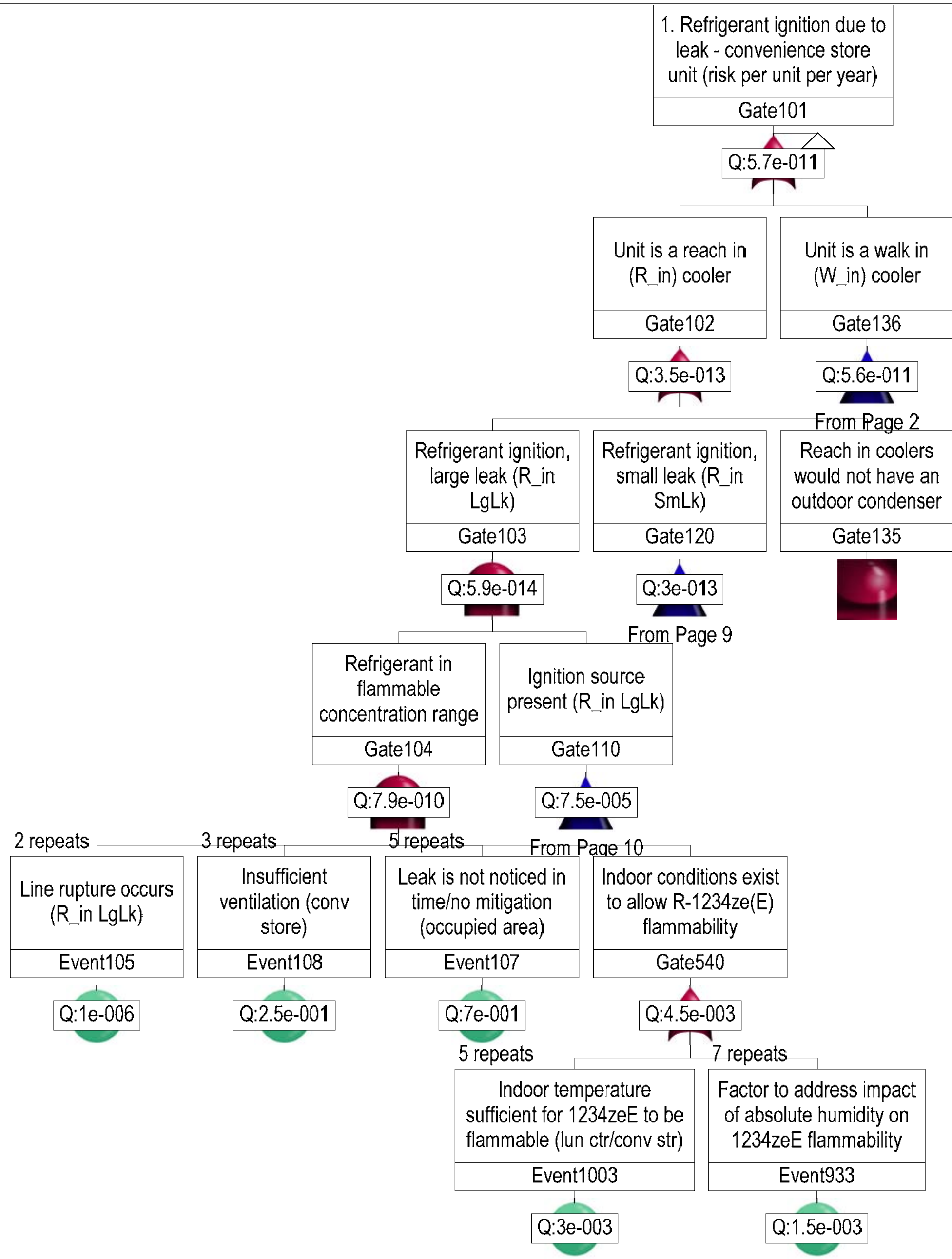


Figure A-26 – Test 21 HFO-1234ze Concentrations

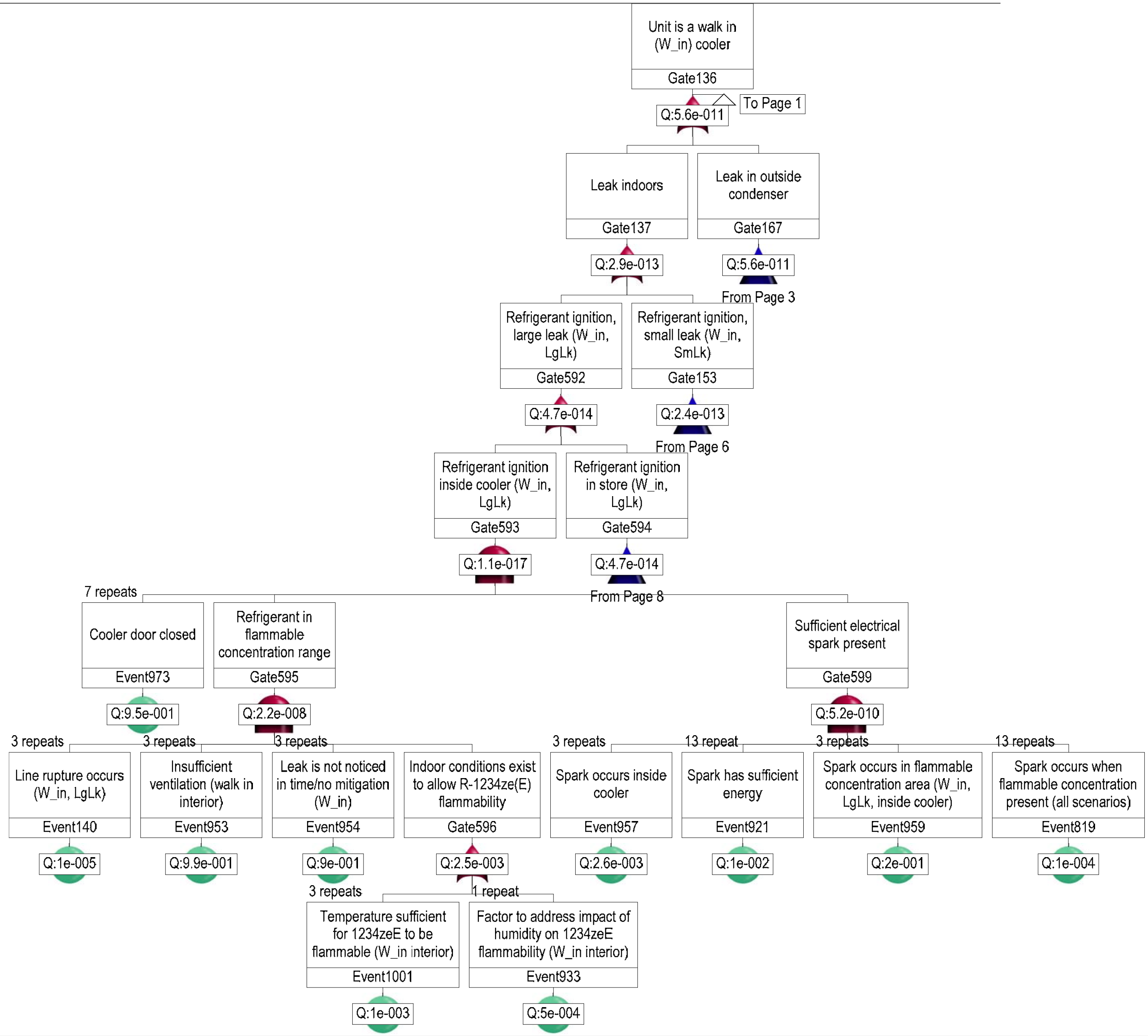
APPENDIX B

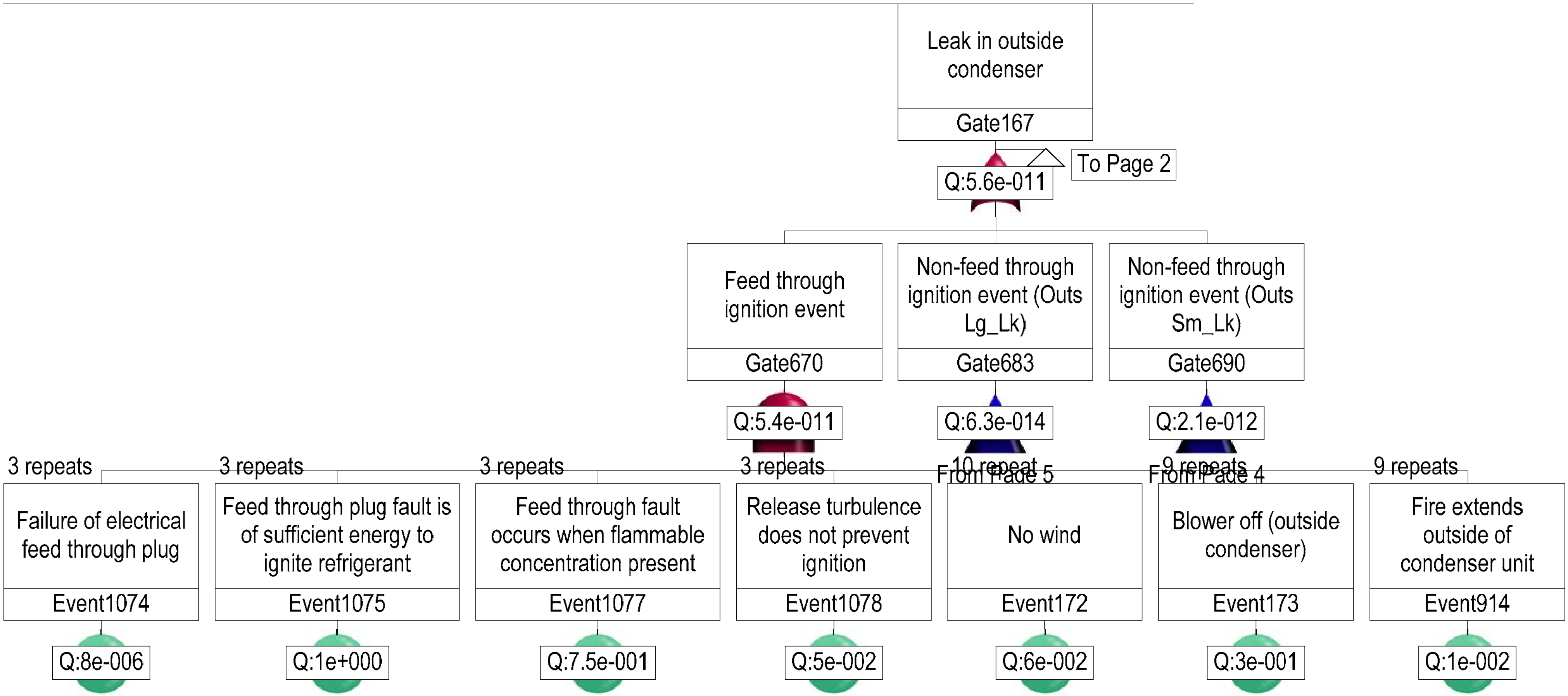
Fault Trees and Input Values Table

FAULT TREES FOR R-1234ze(E)

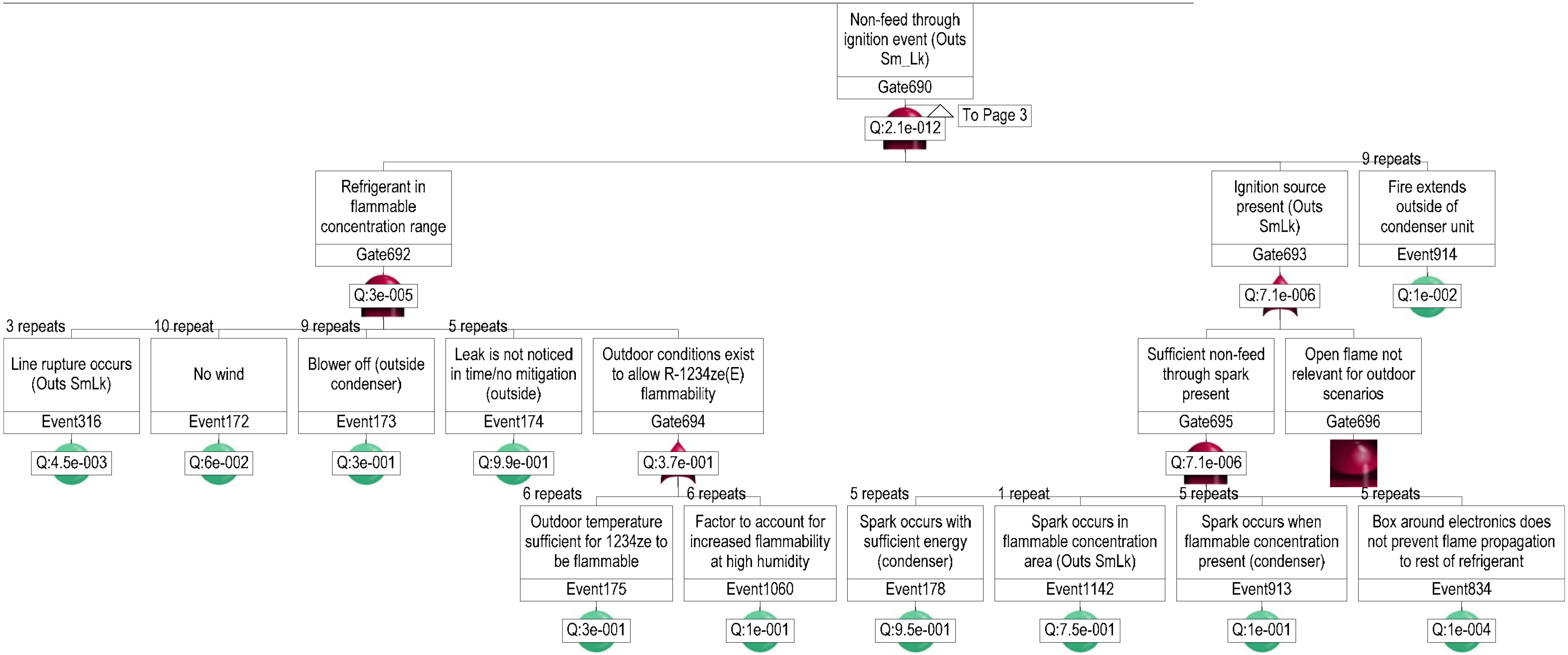

1. Refrigerant ignition due to leak - convenience store unit (risk per unit per year)
Gate101
Q:5.7e-011
Unit is a reach in (R_in) cooler
Gate102
Q:3.5e-013
Unit is a walk in (W_in) cooler
Gate136
Q:5.6e-011
From Page 2
Refrigerant ignition, large leak (R_in LgLk)
Gate103
Q:5.9e-014
Refrigerant ignition, small leak (R_in SmLk)
Gate120
Q:3e-013
From Page 9
Reach in coolers would not have an outdoor condenser
Gate135
Refrigerant in flammable concentration range
Gate104
Q:7.9e-010
Ignition source present (R_in LgLk)
Gate110
Q:7.5e-005
From Page 10
2 repeats
Line rupture occurs (R_in LgLk)
Event105
Q:1e-006
3 repeats
Insufficient ventilation (conv store)
Event108
Q:2.5e-001
5 repeats
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate540
Q:4.5e-003
5 repeats
Indoor temperature sufficient for 1234zeE to be flammable (lun ctr/conv str)
Event1003
Q:3e-003
7 repeats
Factor to address impact of absolute humidity on 1234zeE flammability
Event933
Q:1.5e-003

GRADIENT

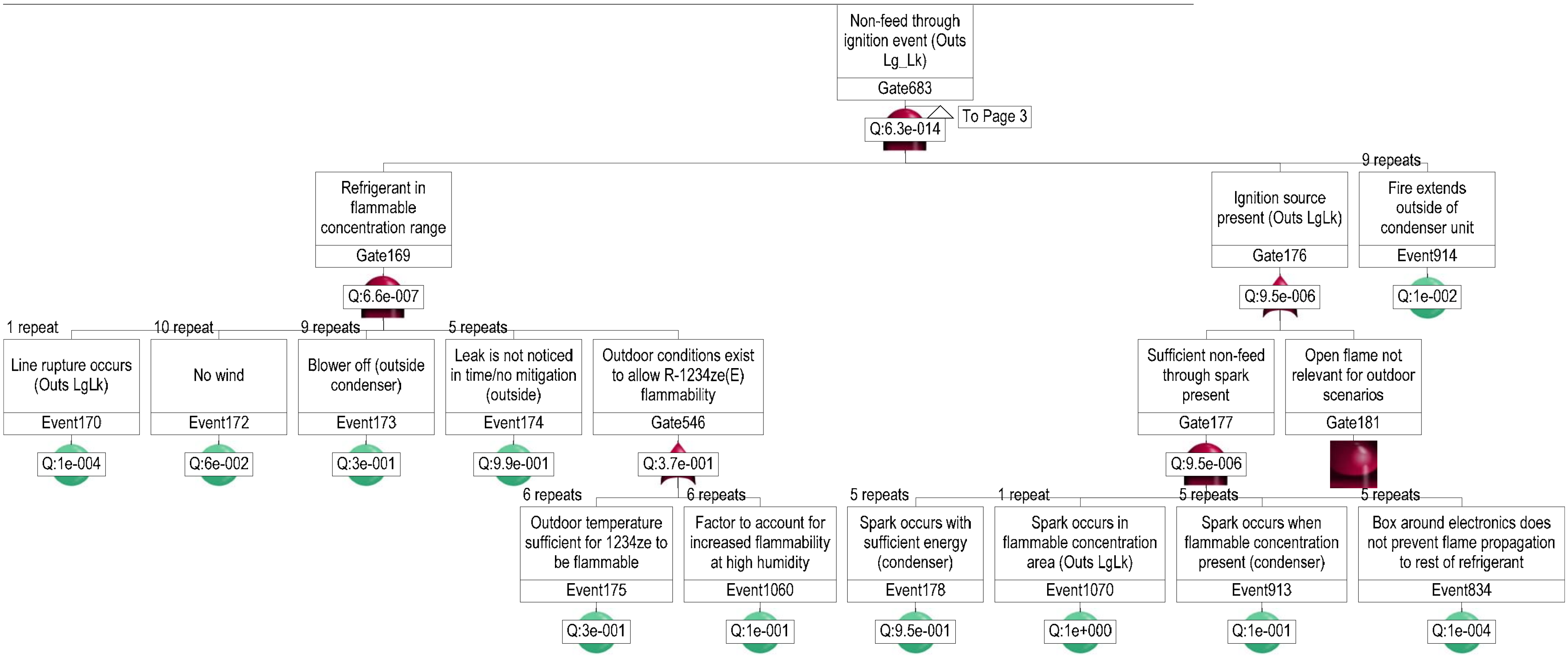

Unit is a walk in (W_in) cooler
Gate136
Q:5.6e-011
To Page 1
Leak indoors
Gate137
Q:2.9e-013
Leak in outside condenser
Gate167
Q:5.6e-011
From Page 3
Refrigerant ignition, large leak (W_in, LgLk)
Gate592
Q:4.7e-014
Refrigerant ignition, small leak (W_in, SmLk)
Gate153
Q:2.4e-013
From Page 6
Refrigerant ignition inside cooler (W_in, LgLk)
Gate593
Q:1.1e-017
Refrigerant ignition in store (W_in, LgLk)
Gate594
Q:4.7e-014
From Page 8
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Refrigerant in flammable concentration range
Gate595
Q:2.2e-008
Sufficient electrical spark present
Gate599
Q:5.2e-010
3 repeats
Line rupture occurs (W_in, LgLk)
Event140
Q:1e-005
3 repeats
Insufficient ventilation (walk in interior)
Event953
Q:9.9e-001
3 repeats
Leak is not noticed in time/no mitigation (W_in)
Event954
Q:9e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate596
Q:2.5e-003
3 repeats
Spark occurs inside cooler
Event957
Q:2.6e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
3 repeats
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)
Event959
Q:2e-001
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
3 repeats
Temperature sufficient for 1234zeE to be flammable (W_in interior)
Event1001
Q:1e-003
1 repeat
Factor to address impact of humidity on 1234zeE flammability (W_in interior)
Event933
Q:5e-004


Leak in outside condenser
Gate167
Q:5.6e-011
To Page 2
Feed through ignition event
Gate670
Q:5.4e-011
Non-feed through ignition event (Outs Lg_Lk)
Gate683
Q:6.3e-014
From Page 5
Non-feed through ignition event (Outs Sm_Lk)
Gate690
Q:2.1e-012
From Page 4
3 repeats
Failure of electrical feed through plug
Event1074
Q:8e-006
3 repeats
Feed through plug fault is of sufficient energy to ignite refrigerant
Event1075
Q:1e+000
3 repeats
Feed through fault occurs when flammable concentration present
Event1077
Q:7.5e-001
3 repeats
Release turbulence does not prevent ignition
Event1078
Q:5e-002
10 repeat
No wind
Event172
Q:6e-002
9 repeats
Blower off (outside condenser)
Event173
Q:3e-001
9 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002

GRADIENT

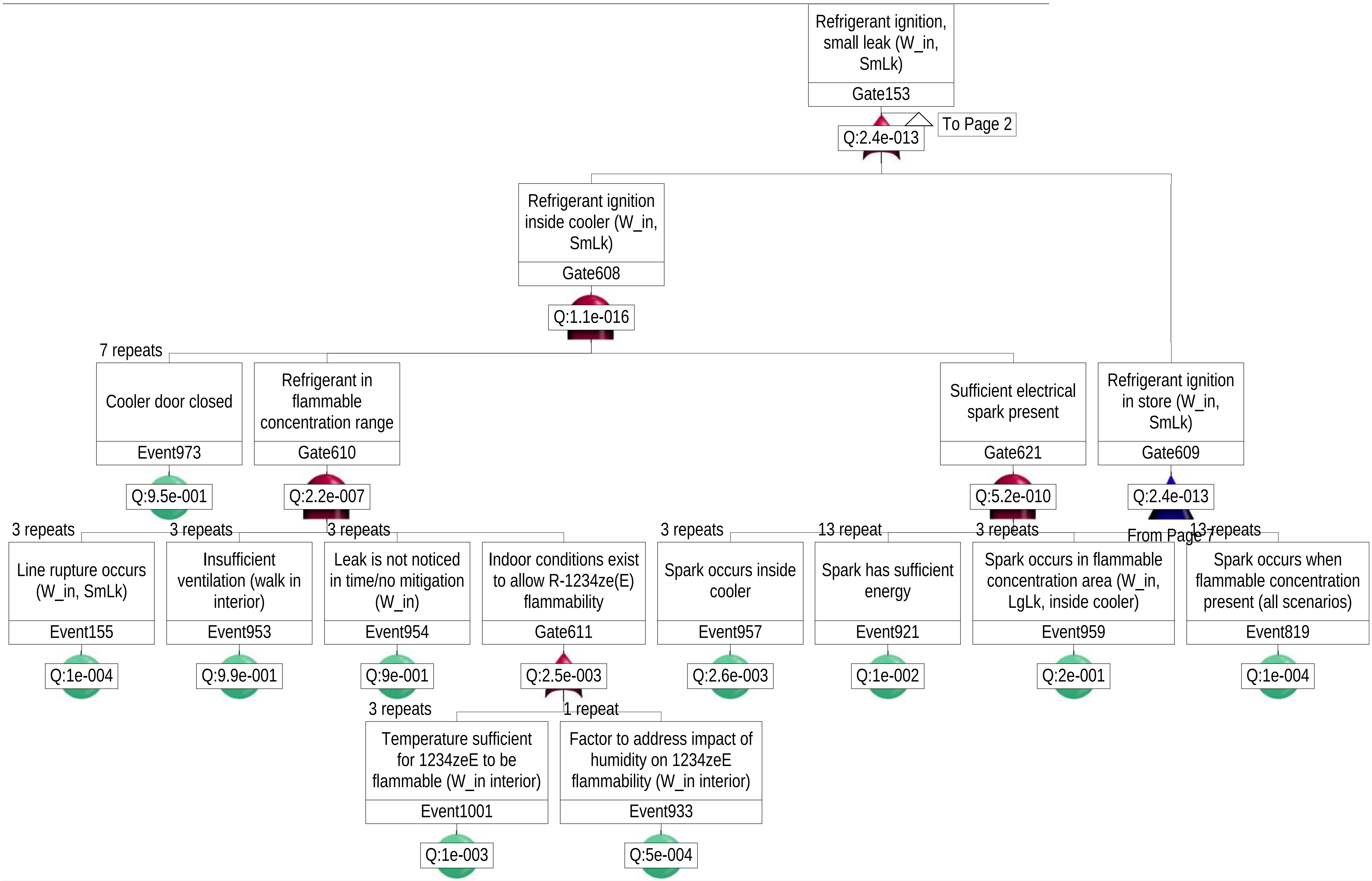

Non-feed through ignition event (Outs Sm_Lk)
Gate690
Q:2.1e-012
To Page 3
Refrigerant in flammable concentration range
Gate692
Q:3e-005
Ignition source present (Outs SmLk)
Gate693
Q:7.1e-006
9 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002
3 repeats
Line rupture occurs (Outs SmLk)
Event316
Q:4.5e-003
10 repeat
No wind
Event172
Q:6e-002
9 repeats
Blower off (outside condenser)
Event173
Q:3e-001
5 repeats
Leak is not noticed in time/no mitigation (outside)
Event174
Q:9.9e-001
Outdoor conditions exist to allow R-1234ze(E) flammability
Gate694
Q:3.7e-001
Sufficient non-feed through spark present
Gate695
Q:7.1e-006
Open flame not relevant for outdoor scenarios
Gate696
6 repeats
Outdoor temperature sufficient for 1234ze to be flammable
Event175
Q:3e-001
6 repeats
Factor to account for increased flammability at high humidity
Event1060
Q:1e-001
5 repeats
Spark occurs with sufficient energy (condenser)
Event178
Q:9.5e-001
1 repeat
Spark occurs in flammable concentration area (Outs SmLk)
Event1142
Q:7.5e-001
5 repeats
Spark occurs when flammable concentration present (condenser)
Event913
Q:1e-001
5 repeats
Box around electronics does not prevent flame propagation to rest of refrigerant
Event834
Q:1e-004

GRADIENT

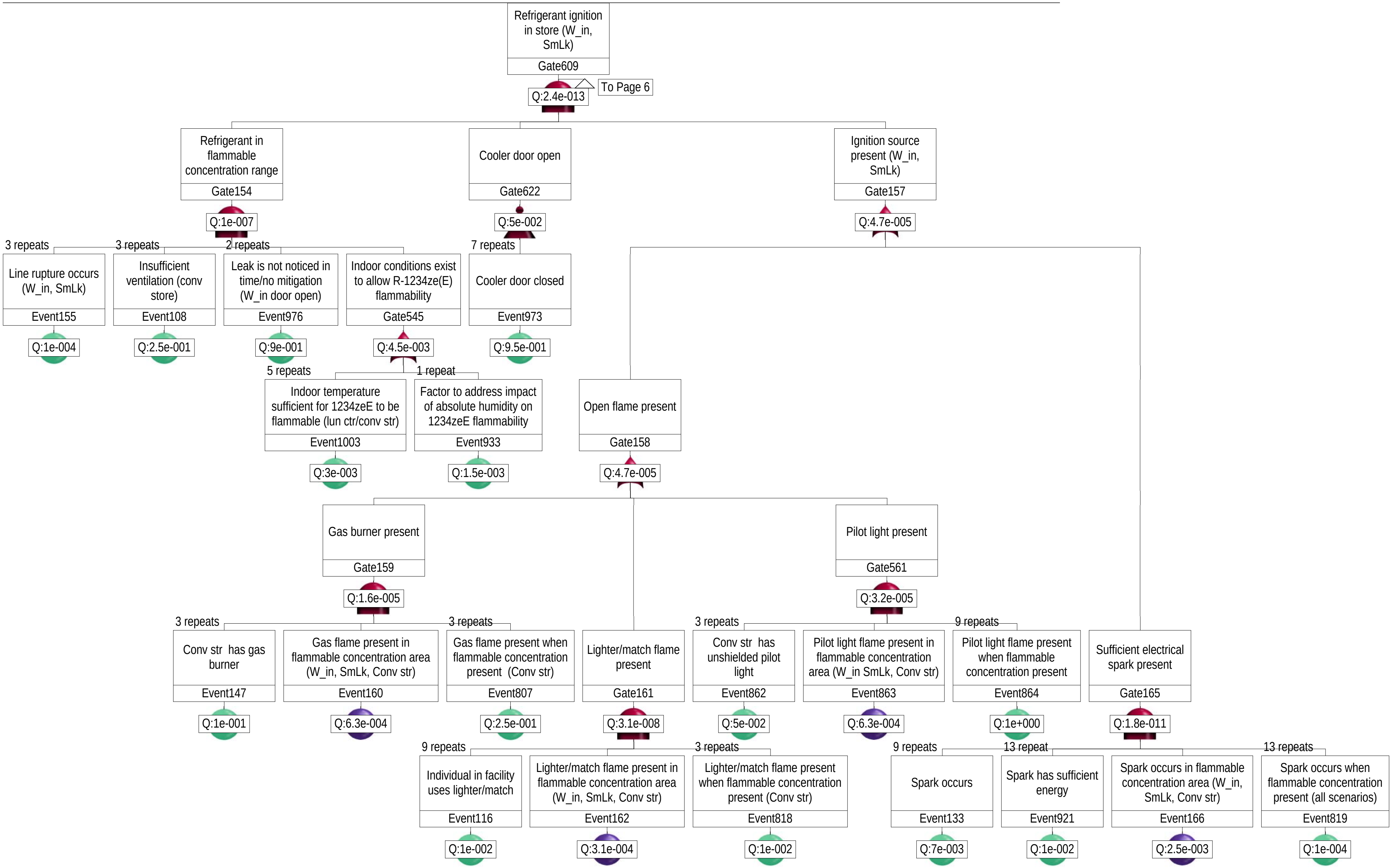


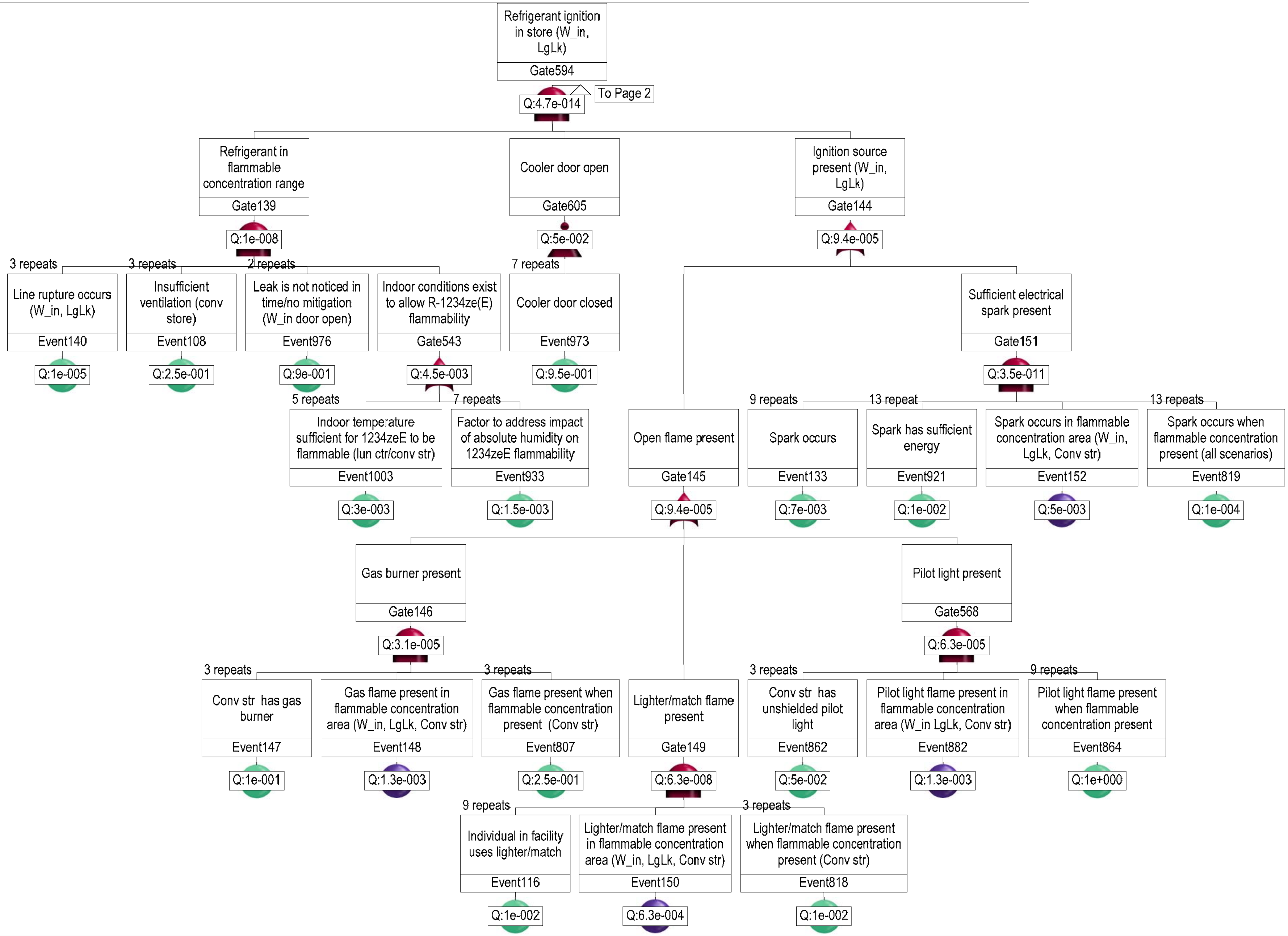
Non-feed through ignition event (Outs Lg_Lk)
Gate683
Q:6.3e-014
To Page 3
Refrigerant in flammable concentration range
Gate169
Q:6.6e-007
Ignition source present (Outs LgLk)
Gate176
Q:9.5e-006
9 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002
1 repeat
Line rupture occurs (Outs LgLk)
Event170
Q:1e-004
10 repeat
No wind
Event172
Q:6e-002
9 repeats
Blower off (outside condenser)
Event173
Q:3e-001
5 repeats
Leak is not noticed in time/no mitigation (outside)
Event174
Q:9.9e-001
Outdoor conditions exist to allow R-1234ze(E) flammability
Gate546
Q:3.7e-001
Sufficient non-feed through spark present
Gate177
Q:9.5e-006
Open flame not relevant for outdoor scenarios
Gate181
6 repeats
Outdoor temperature sufficient for 1234ze to be flammable
Event175
Q:3e-001
6 repeats
Factor to account for increased flammability at high humidity
Event1060
Q:1e-001
5 repeats
Spark occurs with sufficient energy (condenser)
Event178
Q:9.5e-001
1 repeat
Spark occurs in flammable concentration area (Outs LgLk)
Event1070
Q:1e+000
5 repeats
Spark occurs when flammable concentration present (condenser)
Event913
Q:1e-001
5 repeats
Box around electronics does not prevent flame propagation to rest of refrigerant
Event834
Q:1e-004

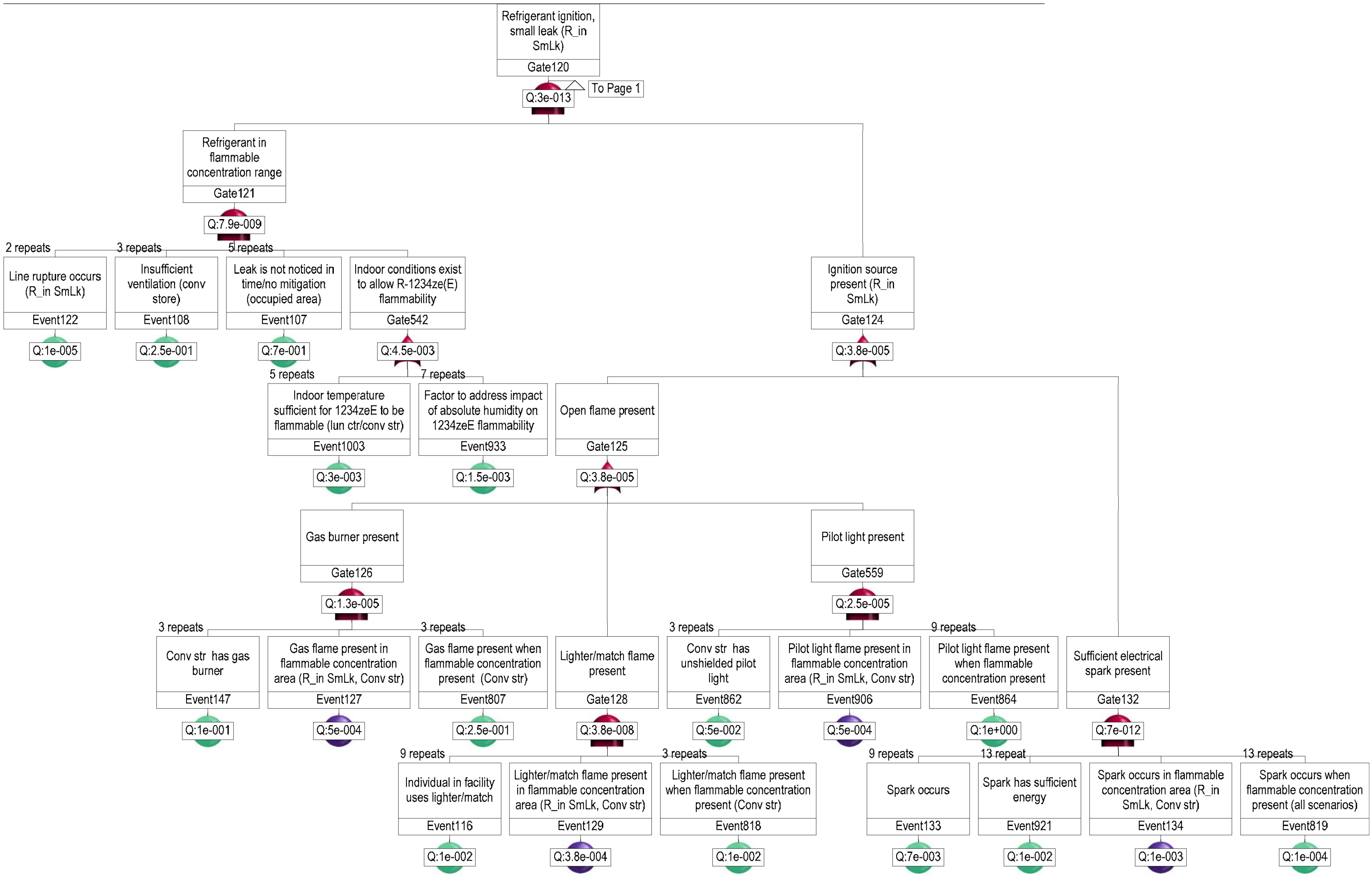
GRADIENT


Refrigerant ignition, small leak (W_in, SmLk)
Gate153
Q:2.4e-013
To Page 2
Refrigerant ignition inside cooler (W_in, SmLk)
Gate608
Q:1.1e-016
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Refrigerant in flammable concentration range
Gate610
Q:2.2e-007
Sufficient electrical spark present
Gate621
Q:5.2e-010
Refrigerant ignition in store (W_in, SmLk)
Gate609
Q:2.4e-013
From Page 7
3 repeats
Line rupture occurs (W_in, SmLk)
Event155
Q:1e-004
3 repeats
Insufficient ventilation (walk in interior)
Event953
Q:9.9e-001
3 repeats
Leak is not noticed in time/no mitigation (W_in)
Event954
Q:9e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate611
Q:2.5e-003
3 repeats
Spark occurs inside cooler
Event957
Q:2.6e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
3 repeats
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)
Event959
Q:2e-001
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
3 repeats
Temperature sufficient for 1234zeE to be flammable (W_in interior)
Event1001
Q:1e-003
1 repeat
Factor to address impact of humidity on 1234zeE flammability (W_in interior)
Event933
Q:5e-004

GRADIENT


Refrigerant ignition in store (W_in, SmLk)
Gate609
Q:2.4e-013
To Page 6
Refrigerant in flammable concentration range
Gate154
Q:1e-007
Cooler door open
Gate622
Q:5e-002
Ignition source present (W_in, SmLk)
Gate157
Q:4.7e-005
3 repeats
Line rupture occurs (W_in, SmLk)
Event155
Q:1e-004
3 repeats
Insufficient ventilation (conv store)
Event108
Q:2.5e-001
2 repeats
Leak is not noticed in time/no mitigation (W_in door open)
Event976
Q:9e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate545
Q:4.5e-003
7 repeats
Cooler door closed
Event973
Q:9.5e-001
5 repeats
Indoor temperature sufficient for 1234zeE to be flammable (lun ctr/conv str)
Event1003
Q:3e-003
1 repeat
Factor to address impact of absolute humidity on 1234zeE flammability
Event933
Q:1.5e-003
Open flame present
Gate158
Q:4.7e-005
Gas burner present
Gate159
Q:1.6e-005
Pilot light present
Gate561
Q:3.2e-005
3 repeats
Conv str has gas burner
Event147
Q:1e-001
Gas flame present in flammable concentration area (W_in, SmLk, Conv str)
Event160
Q:6.3e-004
3 repeats
Gas flame present when flammable concentration present (Conv str)
Event807
Q:2.5e-001
Lighter/match flame present
Gate161
Q:3.1e-008
3 repeats
Conv str has unshielded pilot light
Event862
Q:5e-002
Pilot light flame present in flammable concentration area (W_in SmLk, Conv str)
Event863
Q:6.3e-004
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
Sufficient electrical spark present
Gate165
Q:1.8e-011
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (W_in, SmLk, Conv str)
Event162
Q:3.1e-004
3 repeats
Lighter/match flame present when flammable concentration present (Conv str)
Event818
Q:1e-002
9 repeats
Spark occurs
Event133
Q:7e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (W_in, SmLk, Conv str)
Event166
Q:2.5e-003
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004


Refrigerant ignition in store (W_in, LgLk)
Gate594
Q:4.7e-014
To Page 2
Refrigerant in flammable concentration range
Gate139
Q:1e-008
Cooler door open
Gate605
Q:5e-002
Ignition source present (W_in, LgLk)
Gate144
Q:9.4e-005
3 repeats
Line rupture occurs (W_in, LgLk)
Event140
Q:1e-005
3 repeats
Insufficient ventilation (conv store)
Event108
Q:2.5e-001
2 repeats
Leak is not noticed in time/no mitigation (W_in door open)
Event976
Q:9e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate543
Q:4.5e-003
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Sufficient electrical spark present
Gate151
Q:3.5e-011
5 repeats
Indoor temperature sufficient for 1234zeE to be flammable (lun ctr/conv str)
Event1003
Q:3e-003
7 repeats
Factor to address impact of absolute humidity on 1234zeE flammability
Event933
Q:1.5e-003
Open flame present
Gate145
Q:9.4e-005
9 repeats
Spark occurs
Event133
Q:7e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (W_in, LgLk, Conv str)
Event152
Q:5e-003
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate146
Q:3.1e-005
Pilot light present
Gate568
Q:6.3e-005
3 repeats
Conv str has gas burner
Event147
Q:1e-001
Gas flame present in flammable concentration area (W_in, LgLk, Conv str)
Event148
Q:1.3e-003
3 repeats
Gas flame present when flammable concentration present (Conv str)
Event807
Q:2.5e-001
Lighter/match flame present
Gate149
Q:6.3e-008
3 repeats
Conv str has unshielded pilot light
Event862
Q:5e-002
Pilot light flame present in flammable concentration area (W_in LgLk, Conv str)
Event882
Q:1.3e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (W_in, LgLk, Conv str)
Event150
Q:6.3e-004
3 repeats
Lighter/match flame present when flammable concentration present (Conv str)
Event818
Q:1e-002



Refrigerant ignition, small leak (R_in SmLk)
Gate120
Q:3e-013
To Page 1
Refrigerant in flammable concentration range
Gate121
Q:7.9e-009
2 repeats
Line rupture occurs (R_in SmLk)
Event122
Q:1e-005
3 repeats
Insufficient ventilation (conv store)
Event108
Q:2.5e-001
5 repeats
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate542
Q:4.5e-003
5 repeats
Indoor temperature sufficient for 1234zeE to be flammable (lun ctr/conv str)
Event1003
Q:3e-003
7 repeats
Factor to address impact of absolute humidity on 1234zeE flammability
Event933
Q:1.5e-003
Ignition source present (R_in SmLk)
Gate124
Q:3.8e-005
Open flame present
Gate125
Q:3.8e-005
Gas burner present
Gate126
Q:1.3e-005
Pilot light present
Gate559
Q:2.5e-005
3 repeats
Conv str has gas burner
Event147
Q:1e-001
Gas flame present in flammable concentration area (R_in SmLk, Conv str)
Event127
Q:5e-004
3 repeats
Gas flame present when flammable concentration present (Conv str)
Event807
Q:2.5e-001
Lighter/match flame present
Gate128
Q:3.8e-008
3 repeats
Conv str has unshielded pilot light
Event862
Q:5e-002
Pilot light flame present in flammable concentration area (R_in SmLk, Conv str)
Event906
Q:5e-004
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
Sufficient electrical spark present
Gate132
Q:7e-012
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in SmLk, Conv str)
Event129
Q:3.8e-004
3 repeats
Lighter/match flame present when flammable concentration present (Conv str)
Event818
Q:1e-002
9 repeats
Spark occurs
Event133
Q:7e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (R_in SmLk, Conv str)
Event134
Q:1e-003
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004

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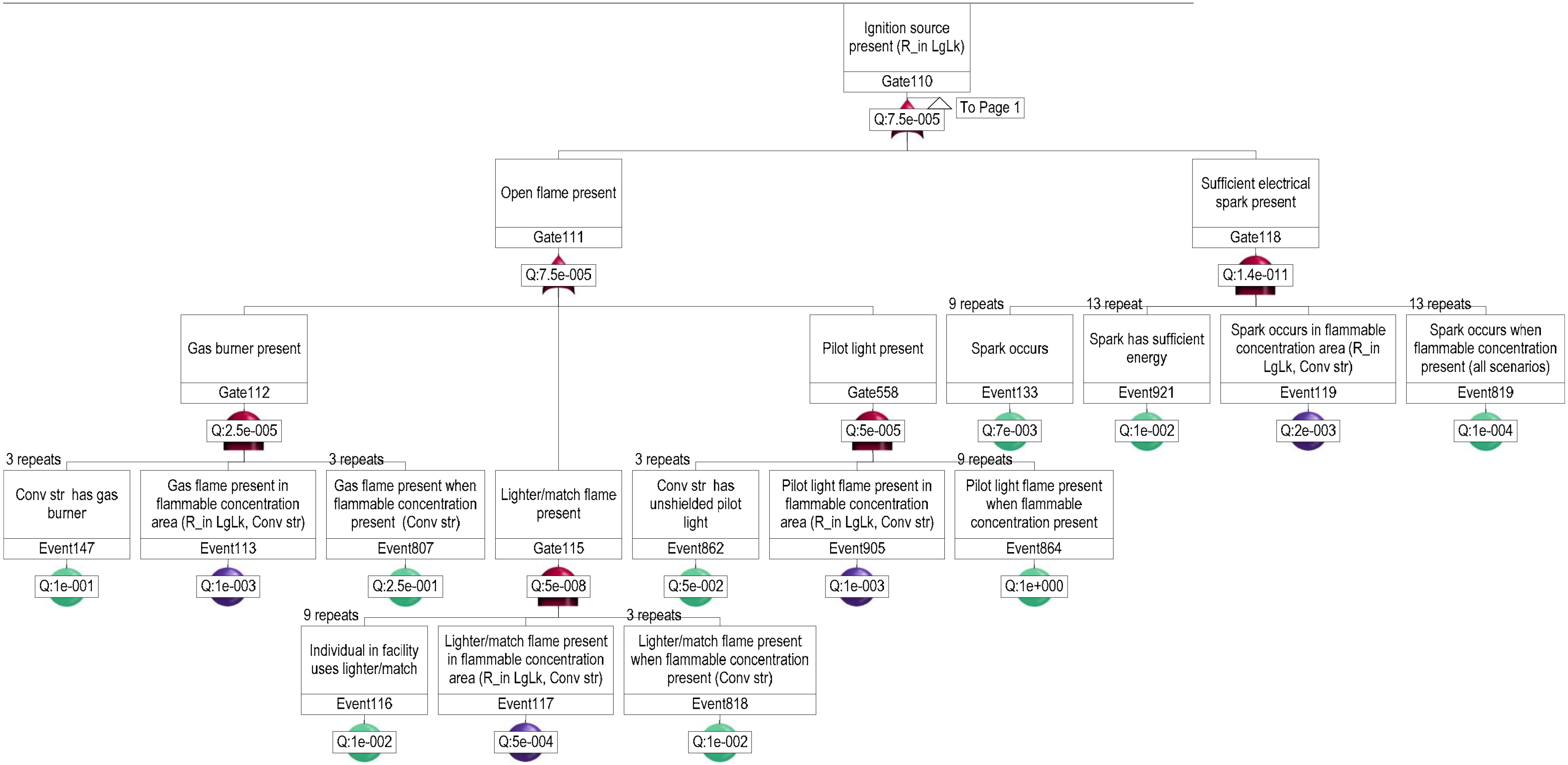
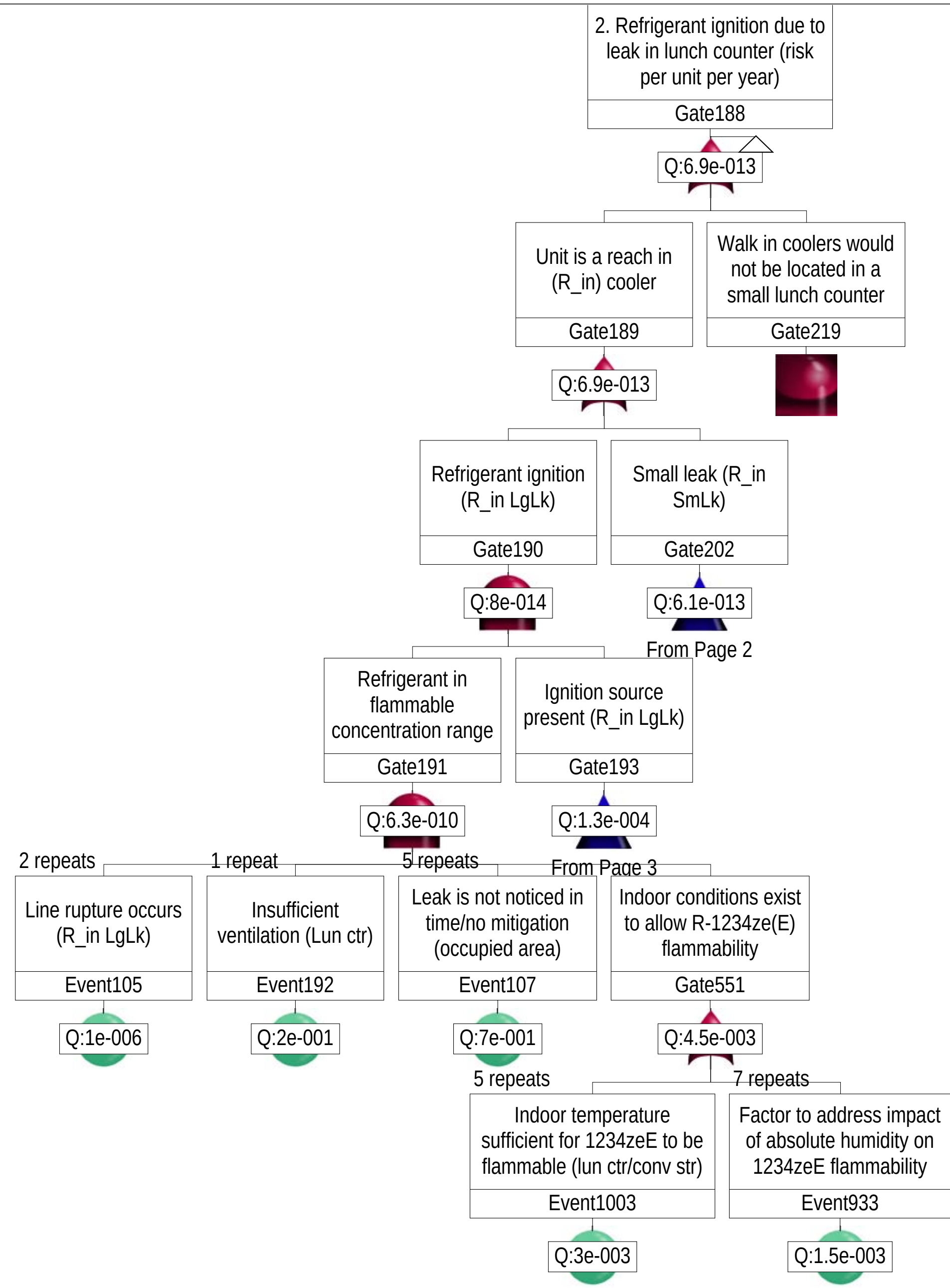
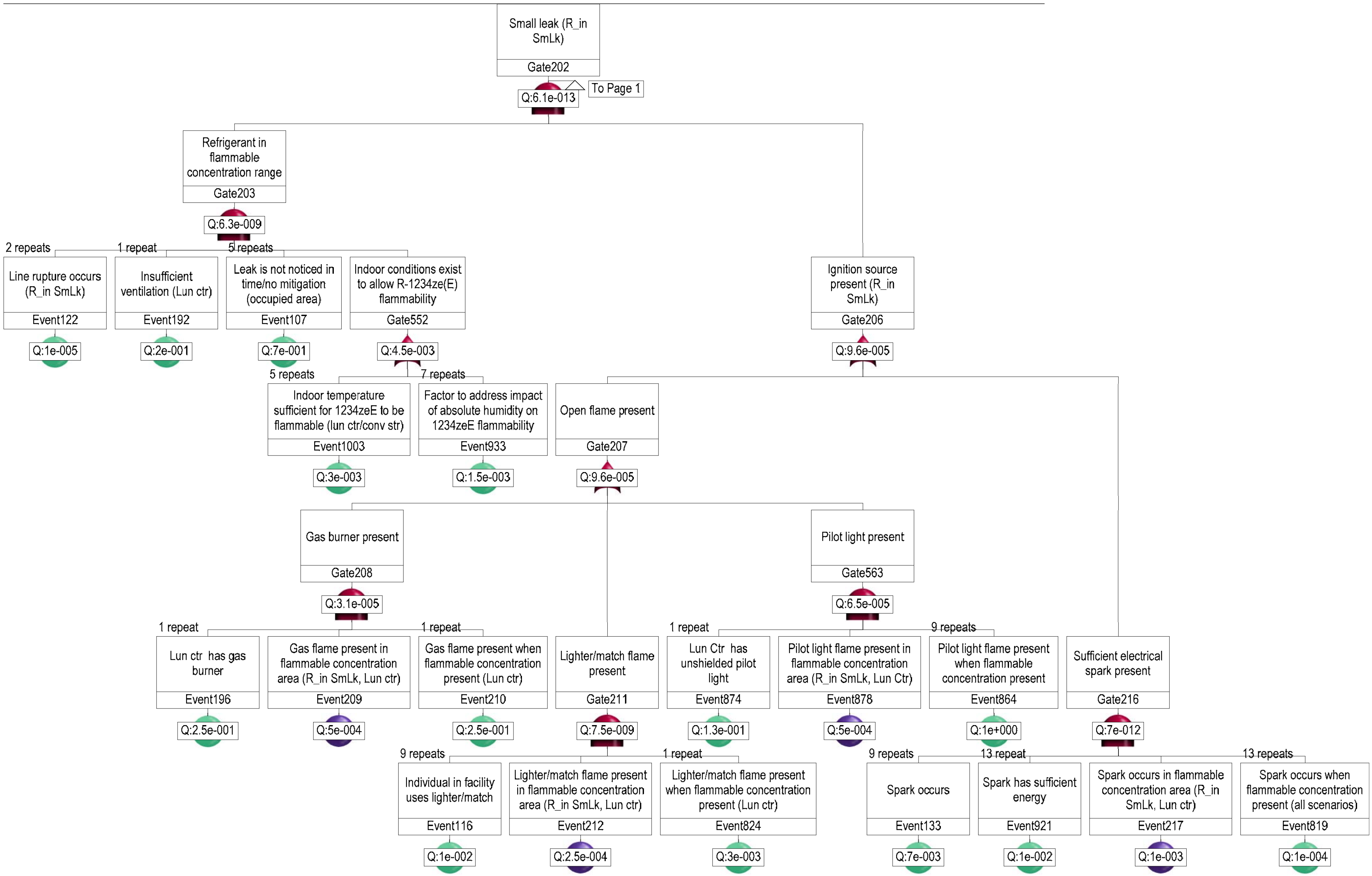

Ignition source present (R_in LgLk)
Gate110
Q:7.5e-005
To Page 1
Open flame present
Gate111
Q:7.5e-005
Sufficient electrical spark present
Gate118
Q:1.4e-011
Gas burner present
Gate112
Q:2.5e-005
Pilot light present
Gate558
Q:5e-005
9 repeats
Spark occurs
Event133
Q:7e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (R_in LgLk, Conv str)
Event119
Q:2e-003
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
3 repeats
Conv str has gas burner
Event147
Q:1e-001
Gas flame present in flammable concentration area (R_in LgLk, Conv str)
Event113
Q:1e-003
3 repeats
Gas flame present when flammable concentration present (Conv str)
Event807
Q:2.5e-001
Lighter/match flame present
Gate115
Q:5e-008
3 repeats
Conv str has unshielded pilot light
Event862
Q:5e-002
Pilot light flame present in flammable concentration area (R_in LgLk, Conv str)
Event905
Q:1e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in LgLk, Conv str)
Event117
Q:5e-004
3 repeats
Lighter/match flame present when flammable concentration present (Conv str)
Event818
Q:1e-002


2. Refrigerant ignition due to leak in lunch counter (risk per unit per year)
Gate188
Q:6.9e-013
Unit is a reach in (R_in) cooler
Gate189
Q:6.9e-013
Walk in coolers would not be located in a small lunch counter
Gate219
Refrigerant ignition (R_in LgLk)
Gate190
Q:8e-014
Small leak (R_in SmLk)
Gate202
Q:6.1e-013
From Page 2
Refrigerant in flammable concentration range
Gate191
Q:6.3e-010
Ignition source present (R_in LgLk)
Gate193
Q:1.3e-004
From Page 3
2 repeats
Line rupture occurs (R_in LgLk)
Event105
Q:1e-006
1 repeat
Insufficient ventilation (Lun ctr)
Event192
Q:2e-001
5 repeats
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate551
Q:4.5e-003
5 repeats
Indoor temperature sufficient for 1234zeE to be flammable (lun ctr/conv str)
Event1003
Q:3e-003
7 repeats
Factor to address impact of absolute humidity on 1234zeE flammability
Event933
Q:1.5e-003

File Name: AHRI Cooler trees Ze 1 2 2015.rfp



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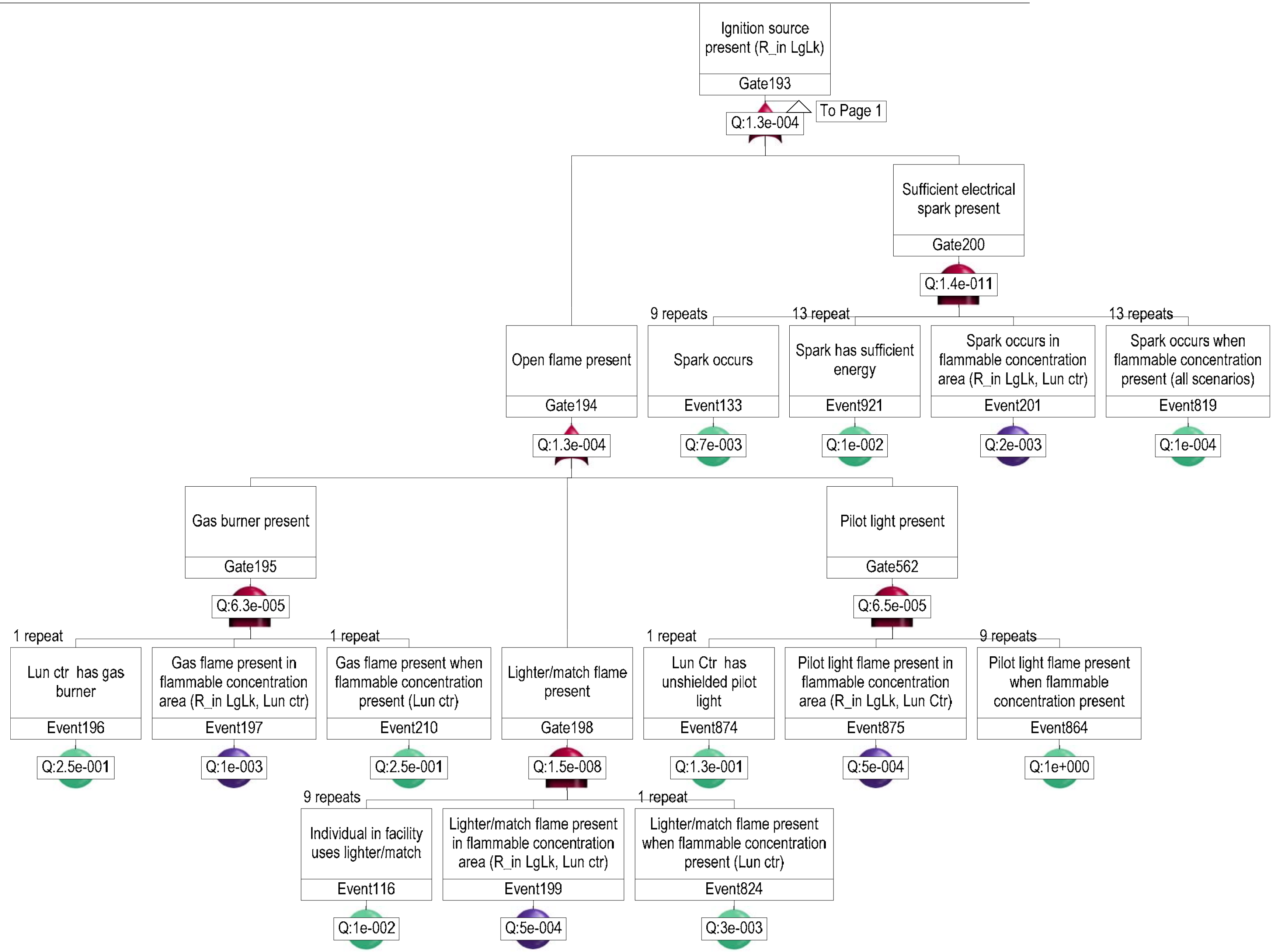
Ignition source present (R_in LgLk)
Gate193
Q:1.3e-004
To Page 1
Sufficient electrical spark present
Gate200
Q:1.4e-011
Open flame present
Gate194
Q:1.3e-004
9 repeats
Spark occurs
Event133
Q:7e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (R_in LgLk, Lun ctr)
Event201
Q:2e-003
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate195
Q:6.3e-005
Pilot light present
Gate562
Q:6.5e-005
1 repeat
Lun ctr has gas burner
Event196
Q:2.5e-001
Gas flame present in flammable concentration area (R_in LgLk, Lun ctr)
Event197
Q:1e-003
1 repeat
Gas flame present when flammable concentration present (Lun ctr)
Event210
Q:2.5e-001
Lighter/match flame present
Gate198
Q:1.5e-008
1 repeat
Lun Ctr has unshielded pilot light
Event874
Q:1.3e-001
Pilot light flame present in flammable concentration area (R_in LgLk, Lun Ctr)
Event875
Q:5e-004
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in LgLk, Lun ctr)
Event199
Q:5e-004
1 repeat
Lighter/match flame present when flammable concentration present (Lun ctr)
Event824
Q:3e-003

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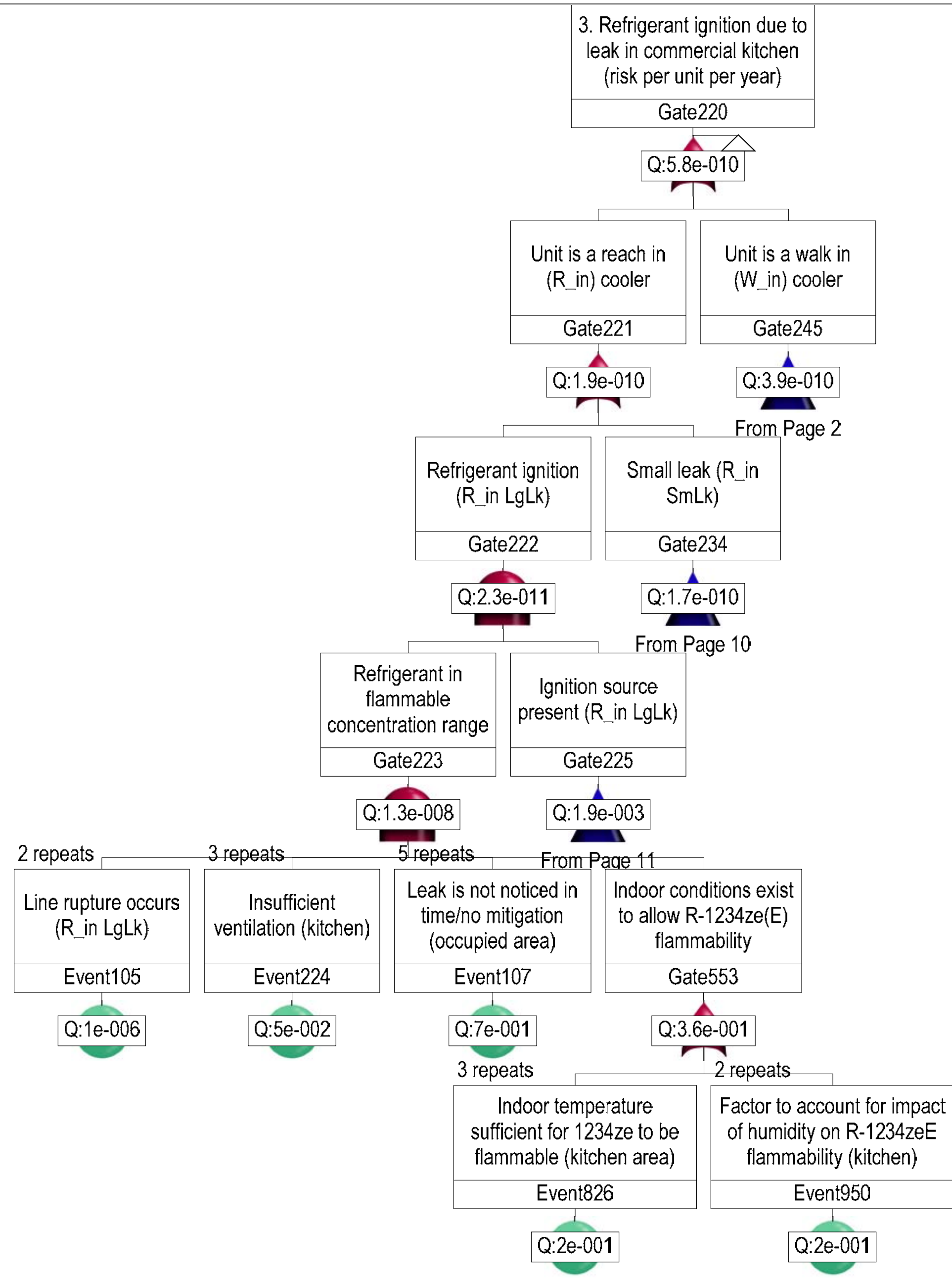
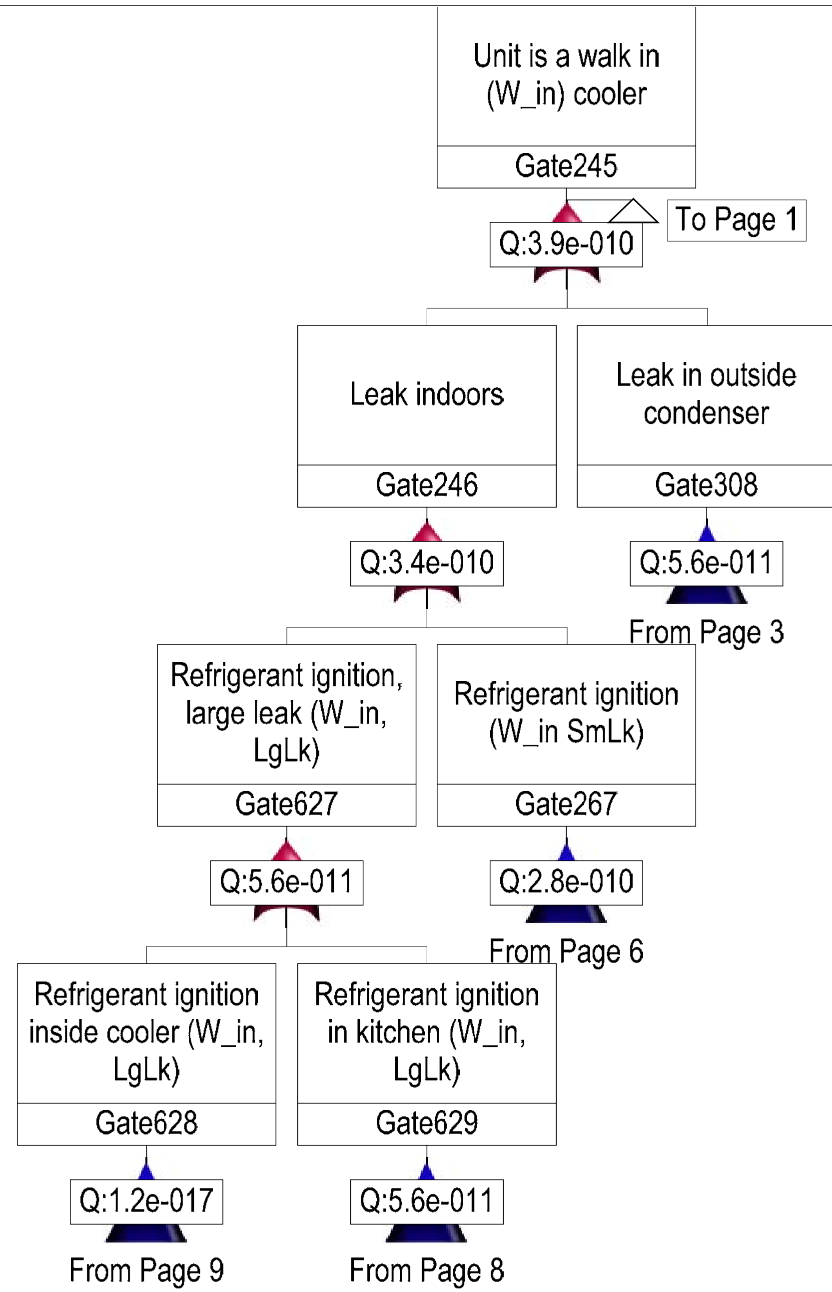
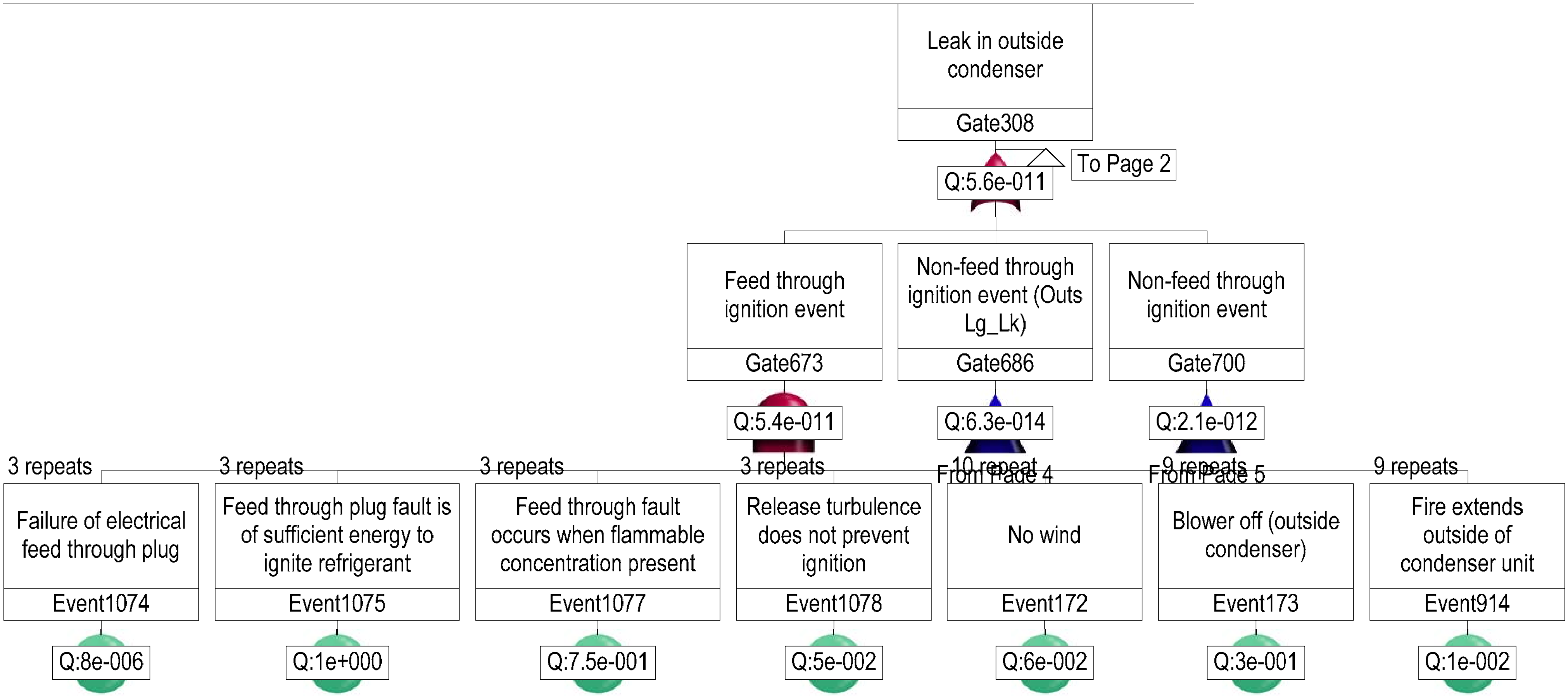

3. Refrigerant ignition due to leak in commercial kitchen (risk per unit per year)
Gate220
Q:5.8e-010
Unit is a reach in (R_in) cooler
Gate221
Q:1.9e-010
Unit is a walk in (W_in) cooler
Gate245
Q:3.9e-010
From Page 2
Refrigerant ignition (R_in LgLk)
Gate222
Q:2.3e-011
Small leak (R_in SmLk)
Gate234
Q:1.7e-010
From Page 10
Refrigerant in flammable concentration range
Gate223
Q:1.3e-008
Ignition source present (R_in LgLk)
Gate225
Q:1.9e-003
From Page 11
2 repeats
Line rupture occurs (R_in LgLk)
Event105
Q:1e-006
3 repeats
Insufficient ventilation (kitchen)
Event224
Q:5e-002
5 repeats
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate553
Q:3.6e-001
3 repeats
Indoor temperature sufficient for 1234ze to be flammable (kitchen area)
Event826
Q:2e-001
2 repeats
Factor to account for impact of humidity on R-1234zeE flammability (kitchen)
Event950
Q:2e-001


Unit is a walk in (W_in) cooler
Gate245
Q:3.9e-010
To Page 1
Leak indoors
Gate246
Q:3.4e-010
Leak in outside condenser
Gate308
Q:5.6e-011
From Page 3
Refrigerant ignition, large leak (W_in, LgLk)
Gate627
Q:5.6e-011
Refrigerant ignition (W_in SmLk)
Gate267
Q:2.8e-010
From Page 6
Refrigerant ignition inside cooler (W_in, LgLk)
Gate628
Q:1.2e-017
From Page 9
Refrigerant ignition in kitchen (W_in, LgLk)
Gate629
Q:5.6e-011
From Page 8



Leak in outside condenser
Gate308
Q:5.6e-011
To Page 2
Feed through ignition event
Gate673
Q:5.4e-011
Non-feed through ignition event (Outs Lg_Lk)
Gate686
Q:6.3e-014
From Page 4
Non-feed through ignition event
Gate700
Q:2.1e-012
From Page 5
3 repeats
Failure of electrical feed through plug
Event1074
Q:8e-006
3 repeats
Feed through plug fault is of sufficient energy to ignite refrigerant
Event1075
Q:1e+000
3 repeats
Feed through fault occurs when flammable concentration present
Event1077
Q:7.5e-001
3 repeats
Release turbulence does not prevent ignition
Event1078
Q:5e-002
10 repeat
No wind
Event172
Q:6e-002
9 repeats
Blower off (outside condenser)
Event173
Q:3e-001
9 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002

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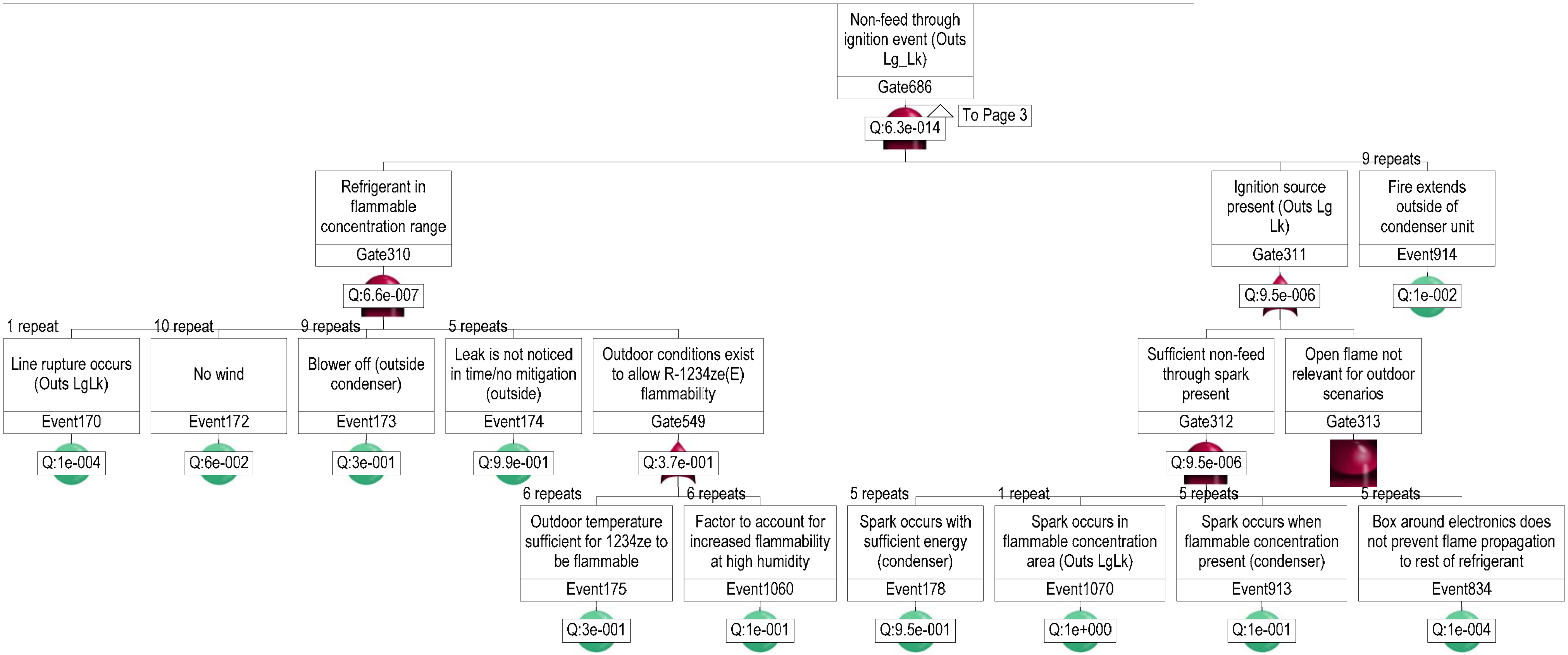
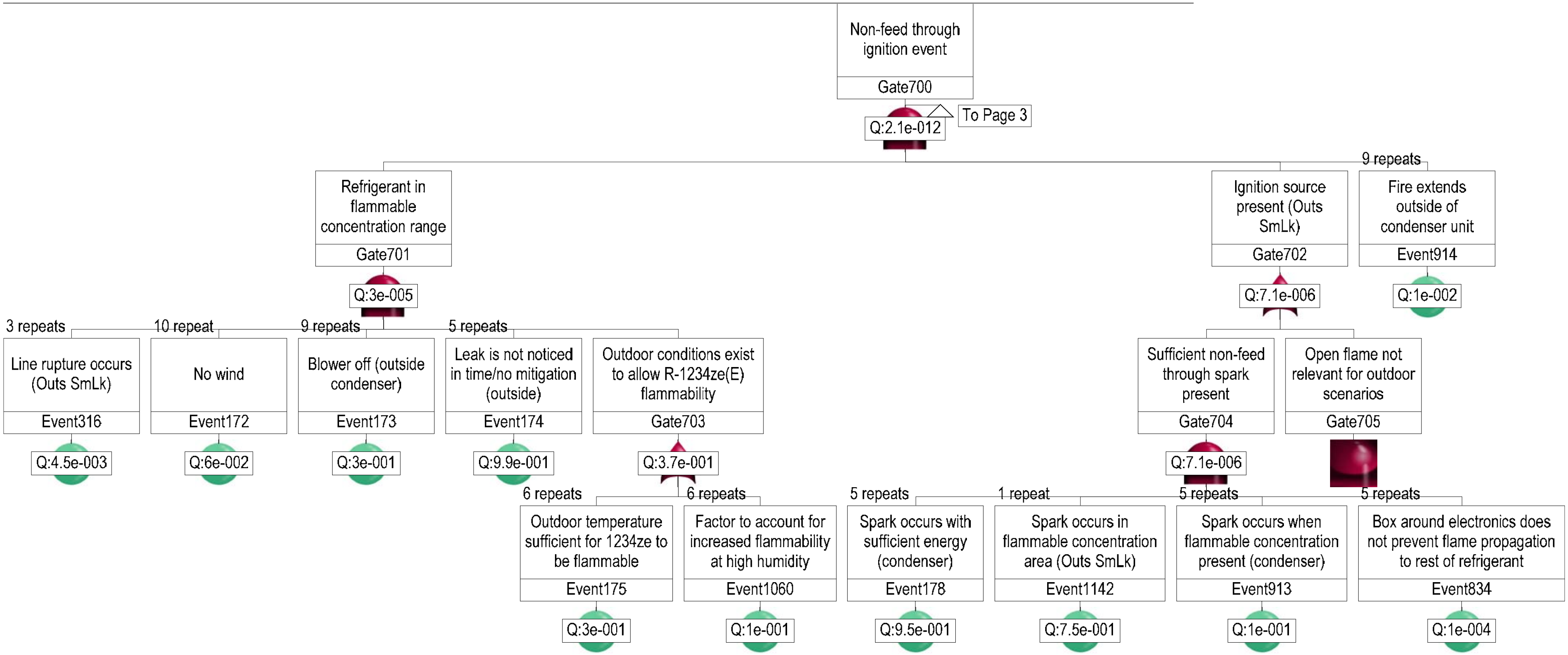
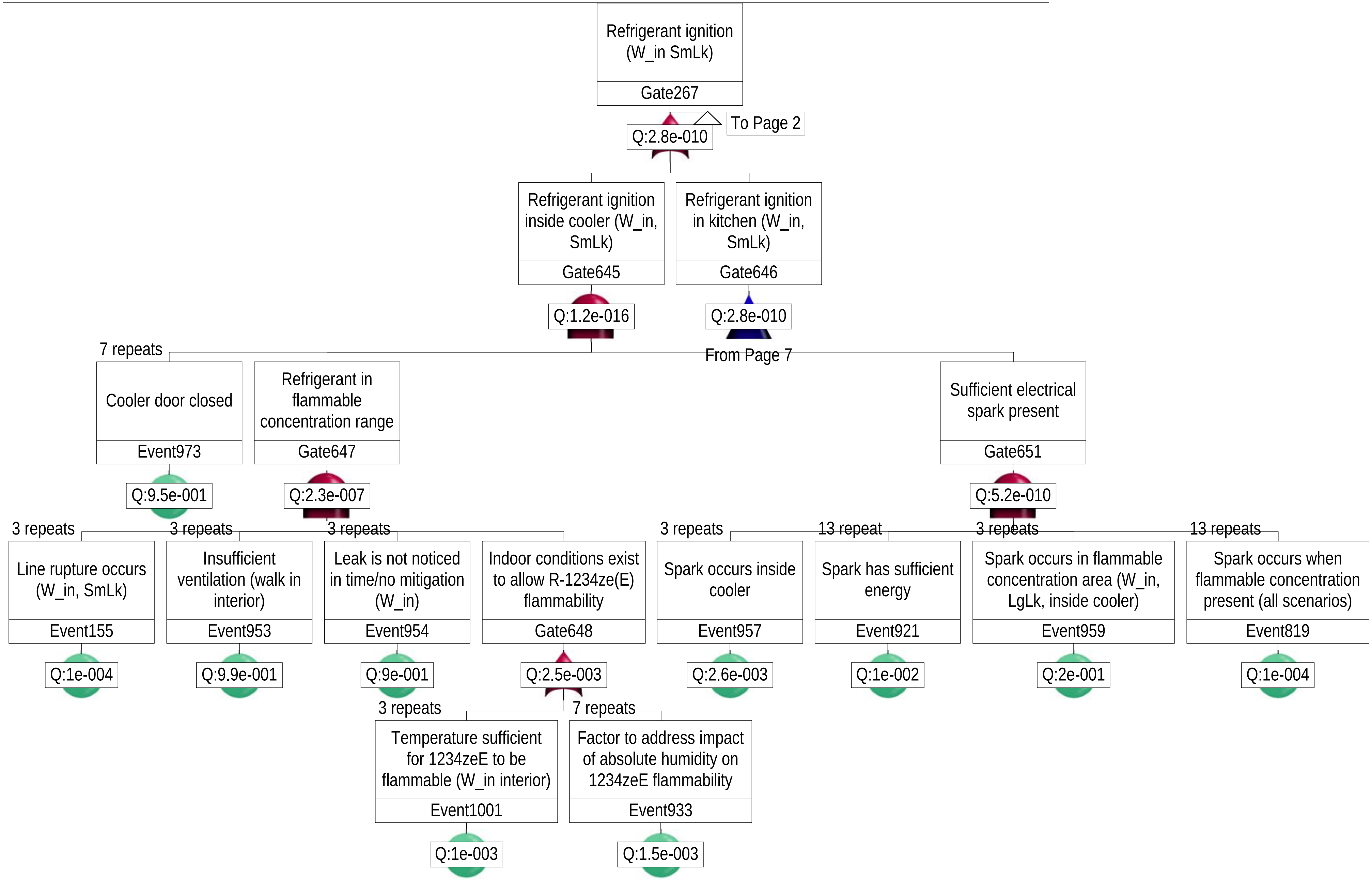
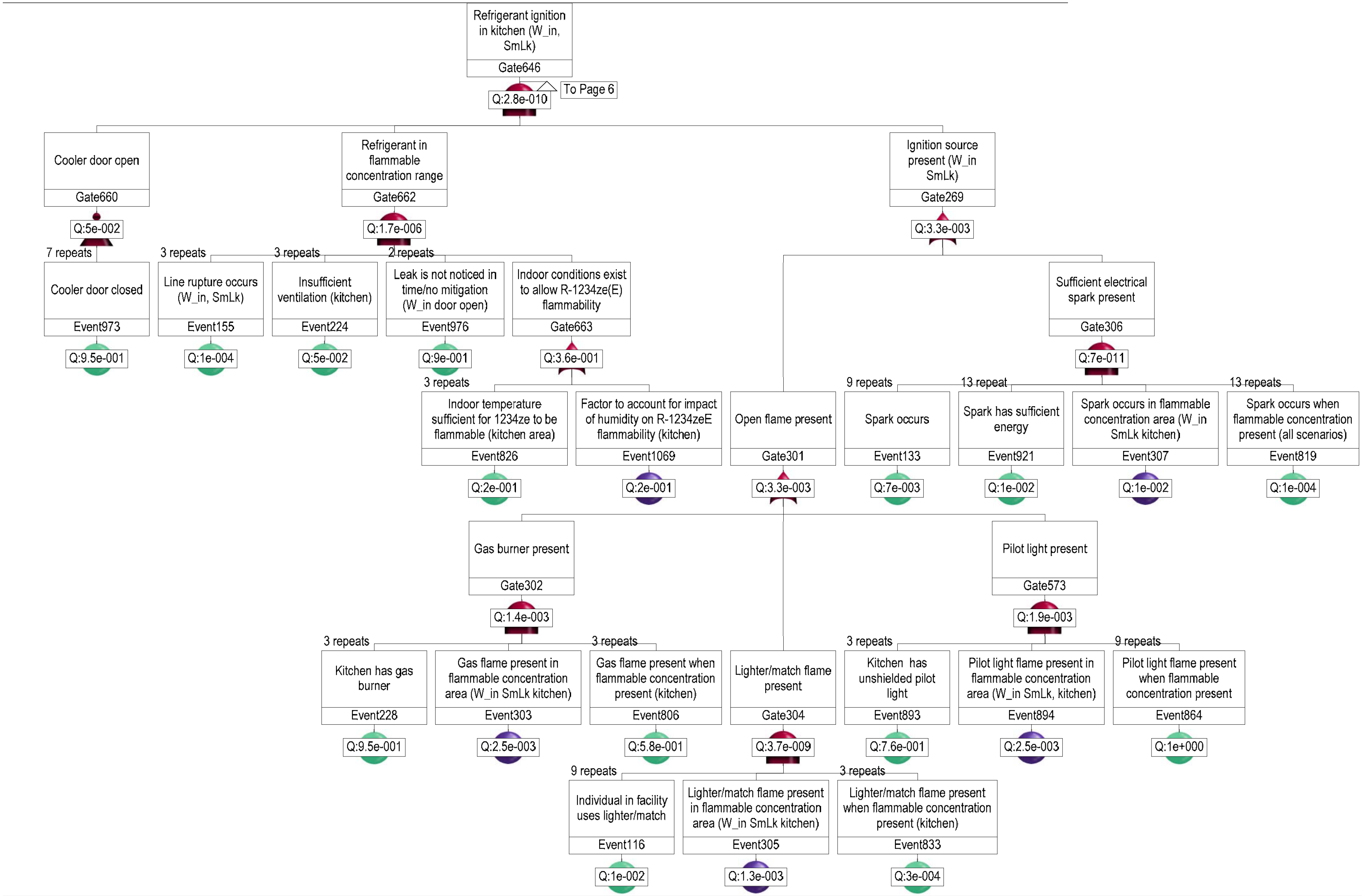
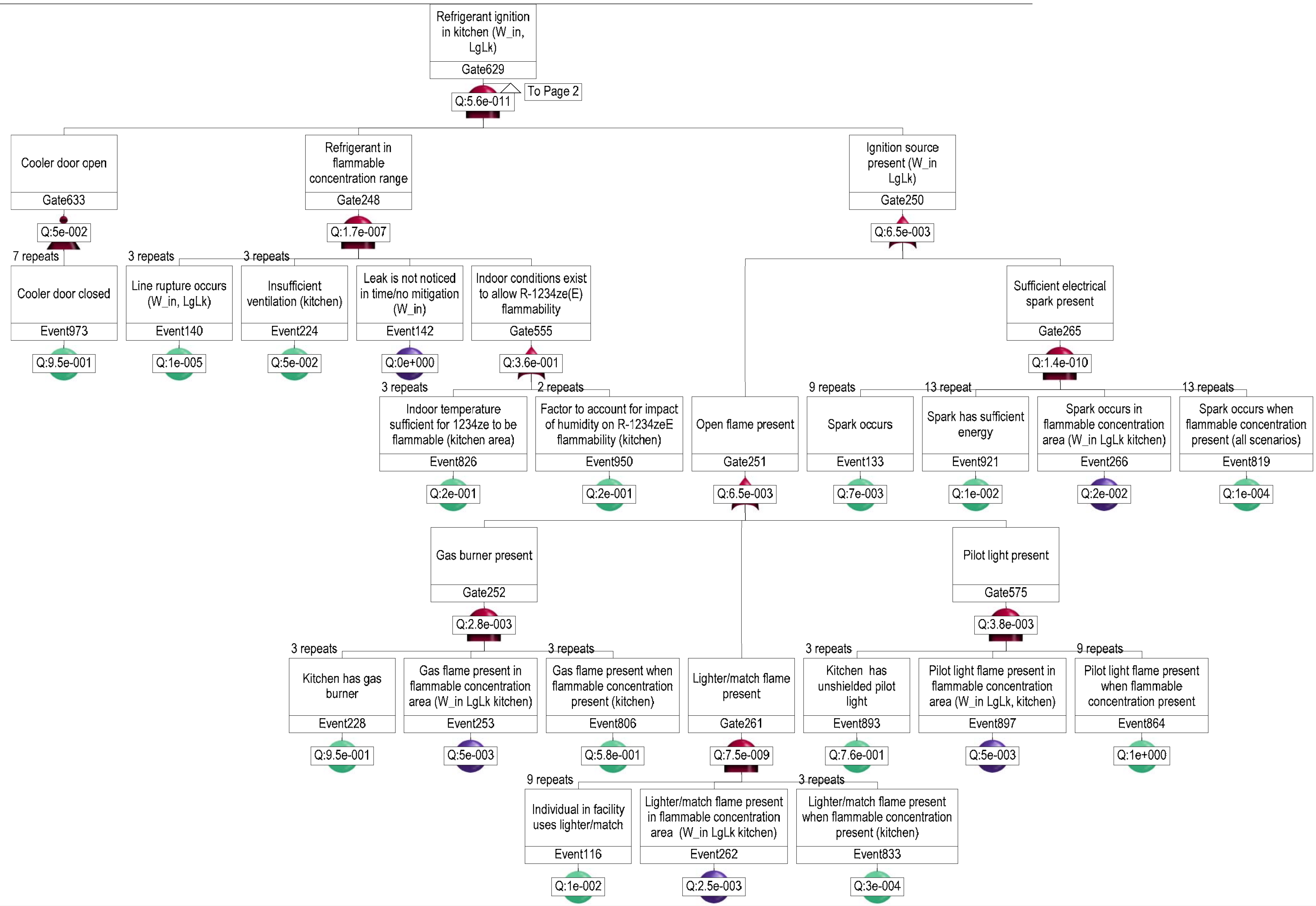

Non-feed through ignition event (Outs Lg_Lk)
Gate686
Q:6.3e-014
To Page 3
Refrigerant in flammable concentration range
Gate310
Q:6.6e-007
Ignition source present (Outs Lg Lk)
Gate311
Q:9.5e-006
9 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002
1 repeat
Line rupture occurs (Outs LgLk)
Event170
Q:1e-004
10 repeat
No wind
Event172
Q:6e-002
9 repeats
Blower off (outside condenser)
Event173
Q:3e-001
5 repeats
Leak is not noticed in time/no mitigation (outside)
Event174
Q:9.9e-001
Outdoor conditions exist to allow R-1234ze(E) flammability
Gate549
Q:3.7e-001
Sufficient non-feed through spark present
Gate312
Q:9.5e-006
Open flame not relevant for outdoor scenarios
Gate313
6 repeats
Outdoor temperature sufficient for 1234ze to be flammable
Event175
Q:3e-001
6 repeats
Factor to account for increased flammability at high humidity
Event1060
Q:1e-001
5 repeats
Spark occurs with sufficient energy (condenser)
Event178
Q:9.5e-001
1 repeat
Spark occurs in flammable concentration area (Outs LgLk)
Event1070
Q:1e+000
5 repeats
Spark occurs when flammable concentration present (condenser)
Event913
Q:1e-001
5 repeats
Box around electronics does not prevent flame propagation to rest of refrigerant
Event834
Q:1e-004

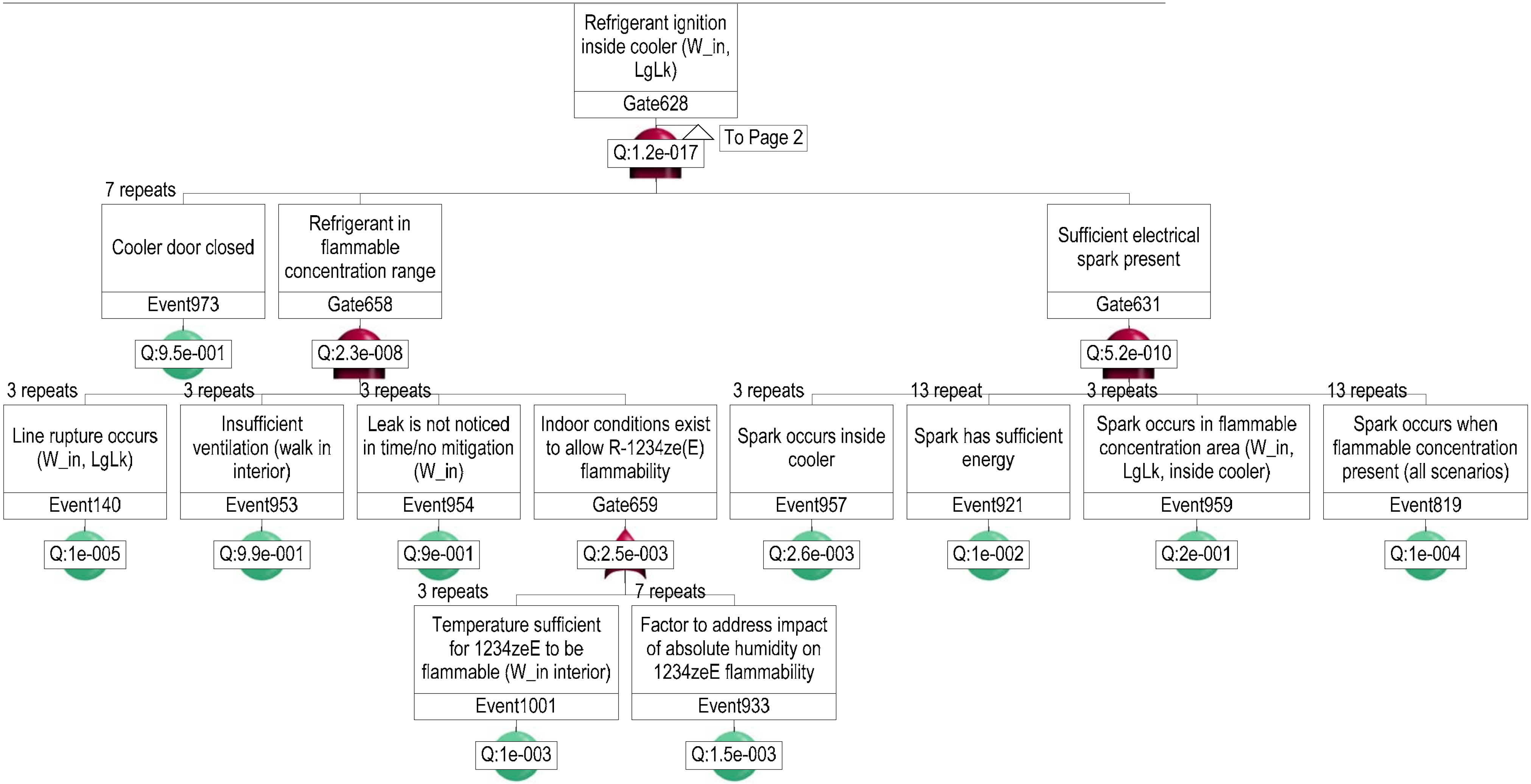

Non-feed through ignition event
Gate700
Q:2.1e-012
To Page 3
Refrigerant in flammable concentration range
Gate701
Q:3e-005
9 repeats
Ignition source present (Outs SmLk)
Gate702
Q:7.1e-006
Fire extends outside of condenser unit
Event914
Q:1e-002
3 repeats
Line rupture occurs (Outs SmLk)
Event316
Q:4.5e-003
10 repeat
No wind
Event172
Q:6e-002
9 repeats
Blower off (outside condenser)
Event173
Q:3e-001
5 repeats
Leak is not noticed in time/no mitigation (outside)
Event174
Q:9.9e-001
Outdoor conditions exist to allow R-1234ze(E) flammability
Gate703
Q:3.7e-001
Sufficient non-feed through spark present
Gate704
Q:7.1e-006
Open flame not relevant for outdoor scenarios
Gate705
6 repeats
Outdoor temperature sufficient for 1234ze to be flammable
Event175
Q:3e-001
6 repeats
Factor to account for increased flammability at high humidity
Event1060
Q:1e-001
5 repeats
Spark occurs with sufficient energy (condenser)
Event178
Q:9.5e-001
1 repeat
Spark occurs in flammable concentration area (Outs SmLk)
Event1142
Q:7.5e-001
5 repeats
Spark occurs when flammable concentration present (condenser)
Event913
Q:1e-001
5 repeats
Box around electronics does not prevent flame propagation to rest of refrigerant
Event834
Q:1e-004

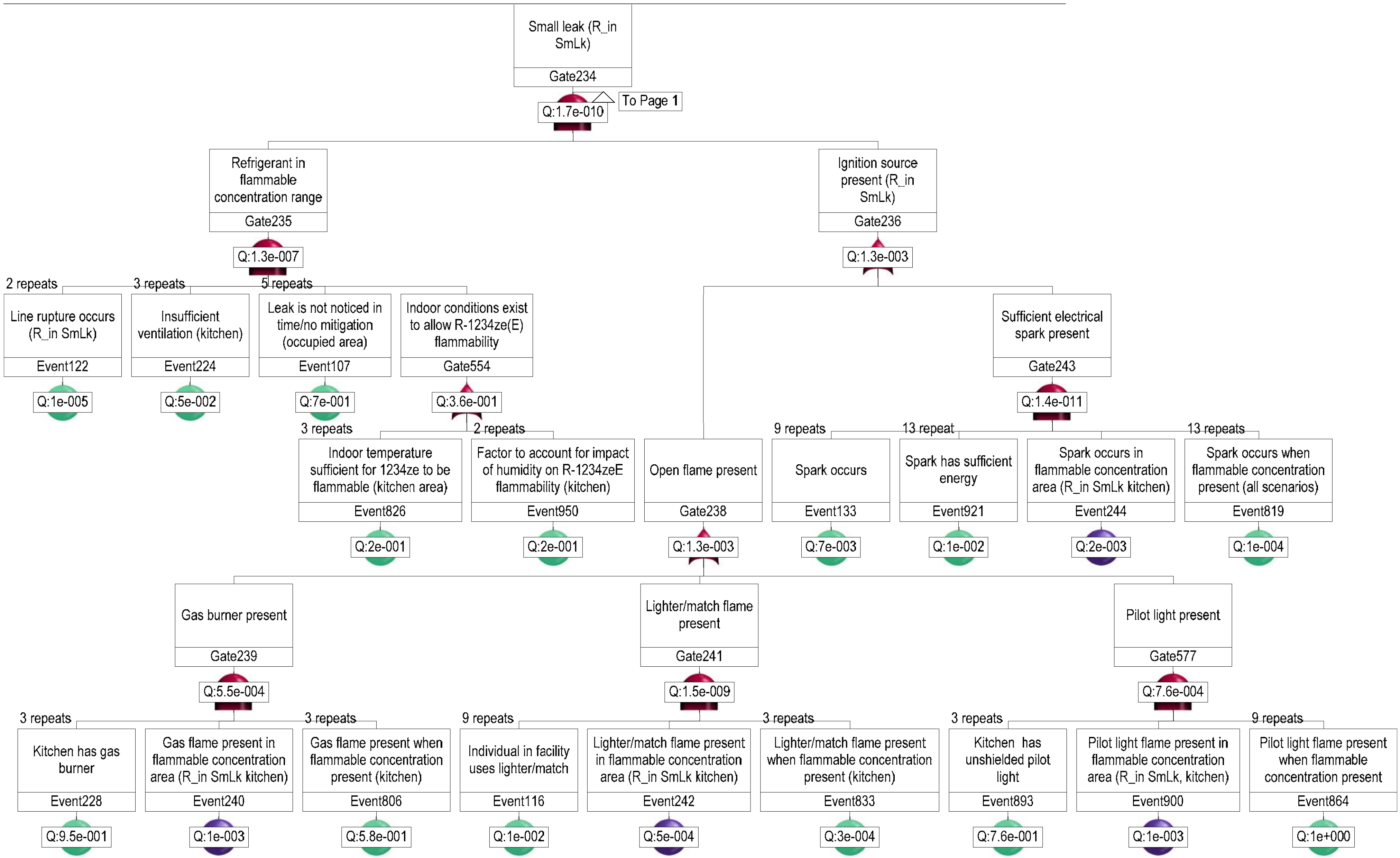

Refrigerant ignition (W_in SmLk)
Gate267
Q:2.8e-010
To Page 2
Refrigerant ignition inside cooler (W_in, SmLk)
Gate645
Q:1.2e-016
Refrigerant ignition in kitchen (W_in, SmLk)
Gate646
Q:2.8e-010
From Page 7
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Refrigerant in flammable concentration range
Gate647
Q:2.3e-007
Sufficient electrical spark present
Gate651
Q:5.2e-010
3 repeats
Line rupture occurs (W_in, SmLk)
Event155
Q:1e-004
3 repeats
Insufficient ventilation (walk in interior)
Event953
Q:9.9e-001
3 repeats
Leak is not noticed in time/no mitigation (W_in)
Event954
Q:9e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate648
Q:2.5e-003
3 repeats
Spark occurs inside cooler
Event957
Q:2.6e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
3 repeats
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)
Event959
Q:2e-001
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
3 repeats
Temperature sufficient for 1234zeE to be flammable (W_in interior)
Event1001
Q:1e-003
7 repeats
Factor to address impact of absolute humidity on 1234zeE flammability
Event933
Q:1.5e-003

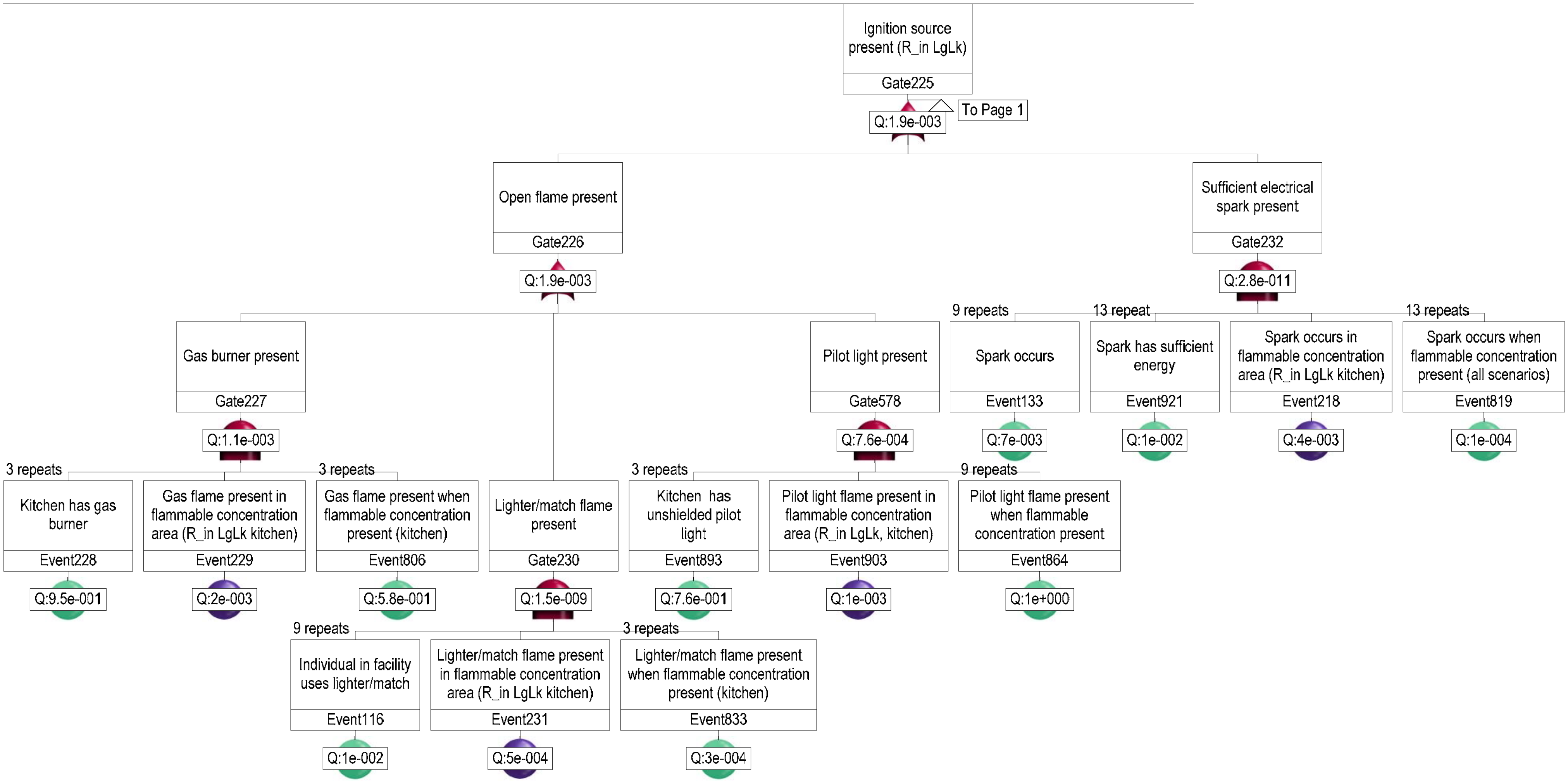

Refrigerant ignition in kitchen (W_in, SmLk)
Gate646
Q:2.8e-010
To Page 6
Cooler door open
Gate660
Q:5e-002
Refrigerant in flammable concentration range
Gate662
Q:1.7e-006
Ignition source present (W_in SmLk)
Gate269
Q:3.3e-003
7 repeats
Cooler door closed
Event973
Q:9.5e-001
3 repeats
Line rupture occurs (W_in, SmLk)
Event155
Q:1e-004
3 repeats
Insufficient ventilation (kitchen)
Event224
Q:5e-002
2 repeats
Leak is not noticed in time/no mitigation (W_in door open)
Event976
Q:9e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate663
Q:3.6e-001
Sufficient electrical spark present
Gate306
Q:7e-011
3 repeats
Indoor temperature sufficient for 1234ze to be flammable (kitchen area)
Event826
Q:2e-001
Factor to account for impact of humidity on R-1234zeE flammability (kitchen)
Event1069
Q:2e-001
Open flame present
Gate301
Q:3.3e-003
9 repeats
Spark occurs
Event133
Q:7e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (W_in SmLk kitchen)
Event307
Q:1e-002
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate302
Q:1.4e-003
Pilot light present
Gate573
Q:1.9e-003
3 repeats
Kitchen has gas burner
Event228
Q:9.5e-001
Gas flame present in flammable concentration area (W_in SmLk kitchen)
Event303
Q:2.5e-003
3 repeats
Gas flame present when flammable concentration present (kitchen)
Event806
Q:5.8e-001
Lighter/match flame present
Gate304
Q:3.7e-009
3 repeats
Kitchen has unshielded pilot light
Event893
Q:7.6e-001
Pilot light flame present in flammable concentration area (W_in SmLk, kitchen)
Event894
Q:2.5e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (W_in SmLk kitchen)
Event305
Q:1.3e-003
3 repeats
Lighter/match flame present when flammable concentration present (kitchen)
Event833
Q:3e-004

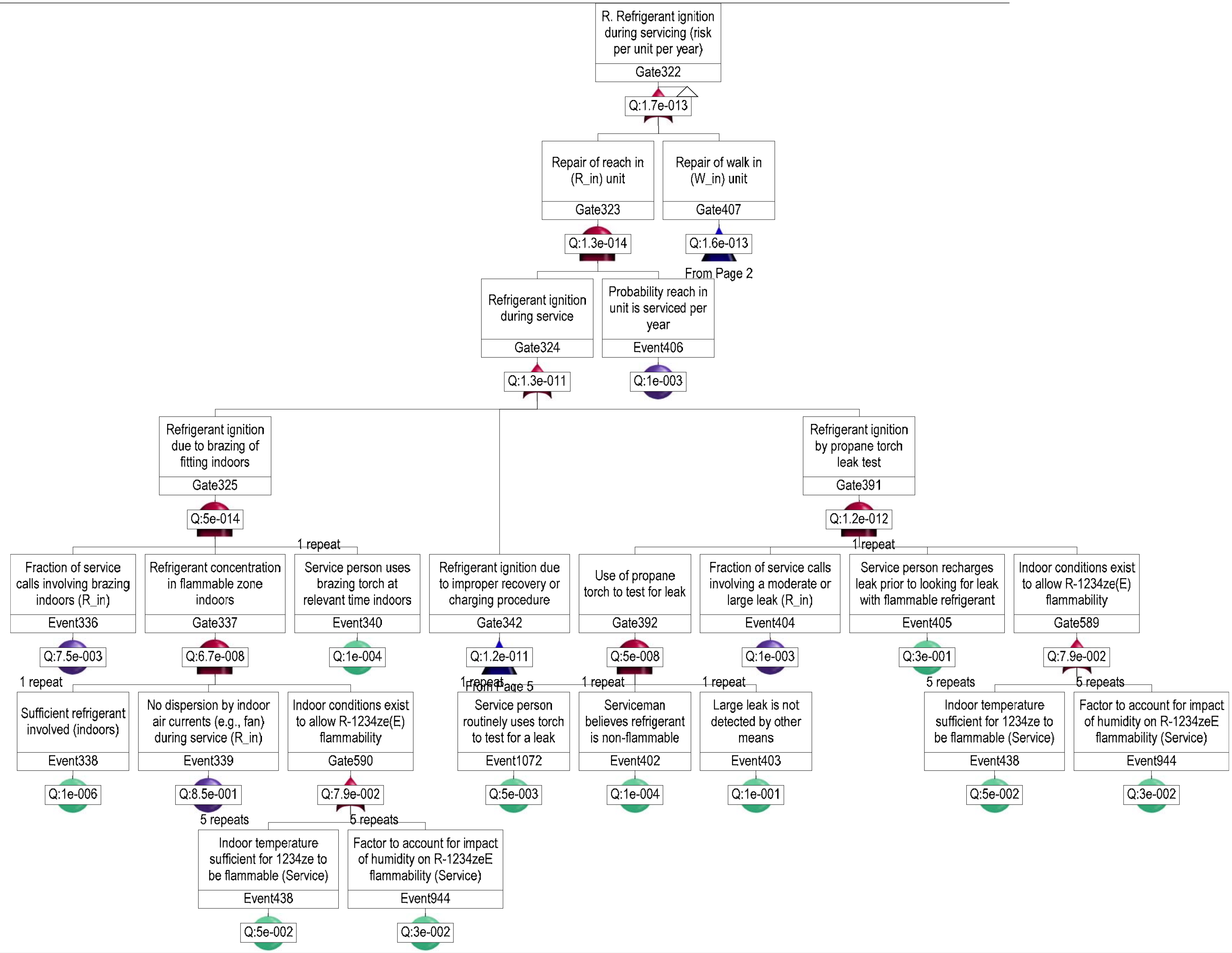

Refrigerant ignition in kitchen (W_in, LgLk)
Gate629
Q:5.6e-011
To Page 2
Cooler door open
Gate633
Q:5e-002
Refrigerant in flammable concentration range
Gate248
Q:1.7e-007
Ignition source present (W_in LgLk)
Gate250
Q:6.5e-003
7 repeats
Cooler door closed
Event973
Q:9.5e-001
3 repeats
Line rupture occurs (W_in, LgLk)
Event140
Q:1e-005
3 repeats
Insufficient ventilation (kitchen)
Event224
Q:5e-002
Leak is not noticed in time/no mitigation (W_in)
Event142
Q:0e+000
Indoor conditions exist to allow R-1234ze(E) flammability
Gate555
Q:3.6e-001
Sufficient electrical spark present
Gate265
Q:1.4e-010
3 repeats
Indoor temperature sufficient for 1234ze to be flammable (kitchen area)
Event826
Q:2e-001
2 repeats
Factor to account for impact of humidity on R-1234zeE flammability (kitchen)
Event950
Q:2e-001
Open flame present
Gate251
Q:6.5e-003
9 repeats
Spark occurs
Event133
Q:7e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (W_in LgLk kitchen)
Event266
Q:2e-002
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate252
Q:2.8e-003
Pilot light present
Gate575
Q:3.8e-003
3 repeats
Kitchen has gas burner
Event228
Q:9.5e-001
Gas flame present in flammable concentration area (W_in LgLk kitchen)
Event253
Q:5e-003
3 repeats
Gas flame present when flammable concentration present (kitchen)
Event806
Q:5.8e-001
Lighter/match flame present
Gate261
Q:7.5e-009
3 repeats
Kitchen has unshielded pilot light
Event893
Q:7.6e-001
Pilot light flame present in flammable concentration area (W_in LgLk, kitchen)
Event897
Q:5e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (W_in LgLk kitchen)
Event262
Q:2.5e-003
3 repeats
Lighter/match flame present when flammable concentration present (kitchen)
Event833
Q:3e-004

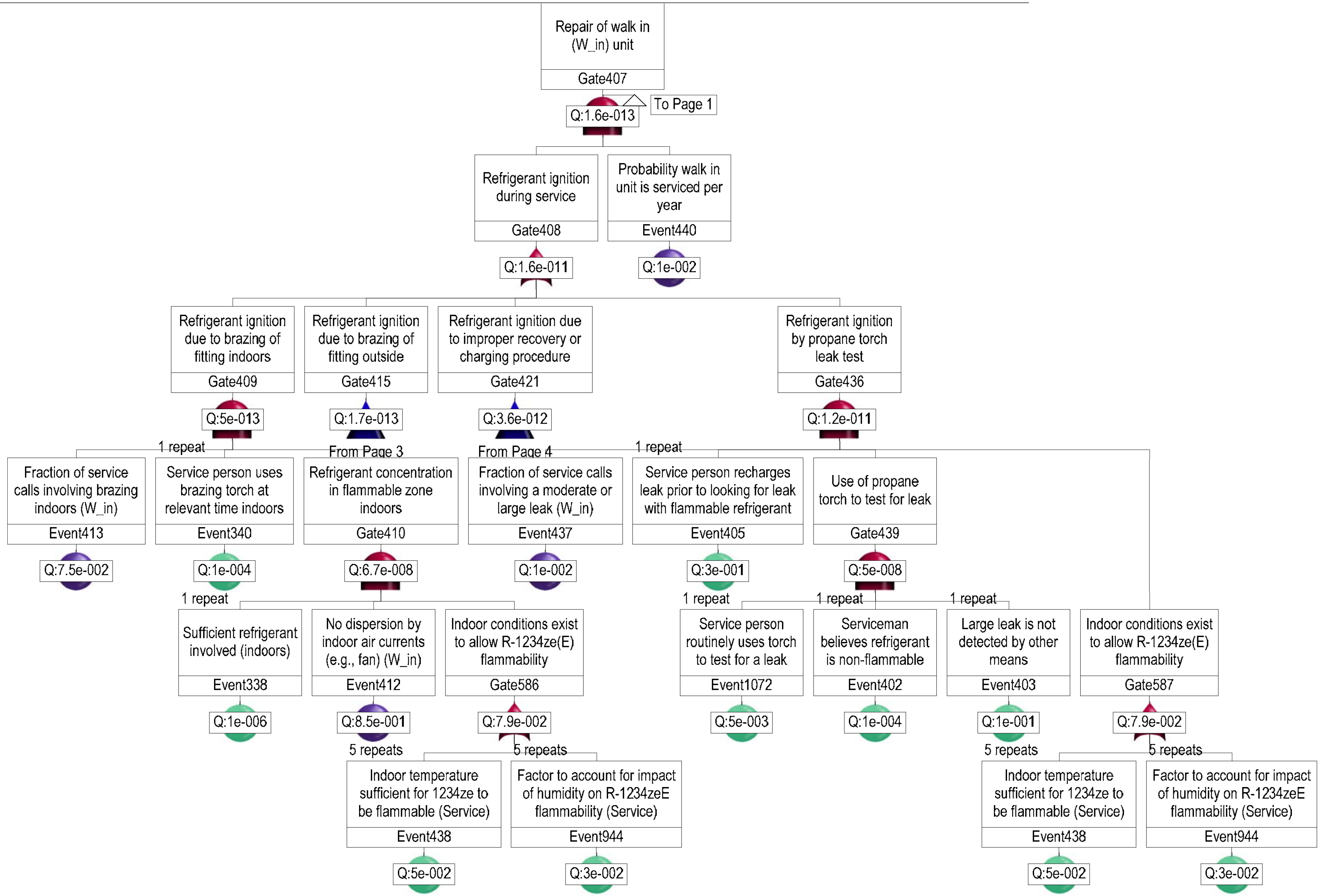
GRADIENT


Refrigerant ignition inside cooler (W_in, LgLk)
Gate628
Q:1.2e-017
To Page 2
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Refrigerant in flammable concentration range
Gate658
Q:2.3e-008
Sufficient electrical spark present
Gate631
Q:5.2e-010
3 repeats
Line rupture occurs (W_in, LgLk)
Event140
Q:1e-005
3 repeats
Insufficient ventilation (walk in interior)
Event953
Q:9.9e-001
3 repeats
Leak is not noticed in time/no mitigation (W_in)
Event954
Q:9e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate659
Q:2.5e-003
3 repeats
Spark occurs inside cooler
Event957
Q:2.6e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
3 repeats
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)
Event959
Q:2e-001
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
3 repeats
Temperature sufficient for 1234zeE to be flammable (W_in interior)
Event1001
Q:1e-003
7 repeats
Factor to address impact of absolute humidity on 1234zeE flammability
Event933
Q:1.5e-003

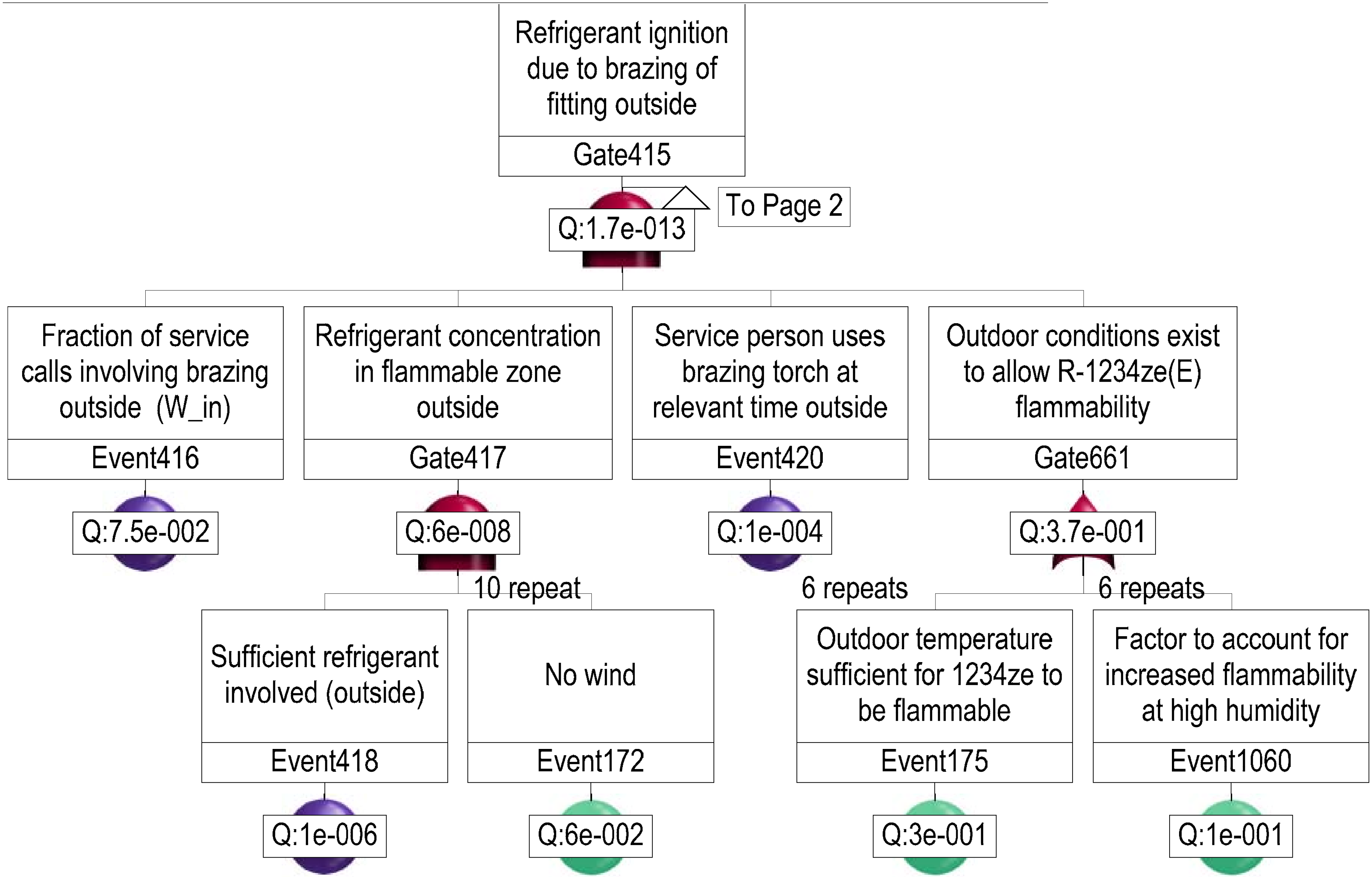

Small leak (R_in SmLk)
Gate234
Q:1.7e-010
To Page 1
Refrigerant in flammable concentration range
Gate235
Q:1.3e-007
Ignition source present (R_in SmLk)
Gate236
Q:1.3e-003
2 repeats
Line rupture occurs (R_in SmLk)
Event122
Q:1e-005
3 repeats
Insufficient ventilation (kitchen)
Event224
Q:5e-002
5 repeats
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate554
Q:3.6e-001
Sufficient electrical spark present
Gate243
Q:1.4e-011
3 repeats
Indoor temperature sufficient for 1234ze to be flammable (kitchen area)
Event826
Q:2e-001
2 repeats
Factor to account for impact of humidity on R-1234zeE flammability (kitchen)
Event950
Q:2e-001
Open flame present
Gate238
Q:1.3e-003
9 repeats
Spark occurs
Event133
Q:7e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (R_in SmLk kitchen)
Event244
Q:2e-003
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate239
Q:5.5e-004
Lighter/match flame present
Gate241
Q:1.5e-009
Pilot light present
Gate577
Q:7.6e-004
3 repeats
Kitchen has gas burner
Event228
Q:9.5e-001
Gas flame present in flammable concentration area (R_in SmLk kitchen)
Event240
Q:1e-003
3 repeats
Gas flame present when flammable concentration present (kitchen)
Event806
Q:5.8e-001
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in SmLk kitchen)
Event242
Q:5e-004
3 repeats
Lighter/match flame present when flammable concentration present (kitchen)
Event833
Q:3e-004
3 repeats
Kitchen has unshielded pilot light
Event893
Q:7.6e-001
Pilot light flame present in flammable concentration area (R_in SmLk, kitchen)
Event900
Q:1e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000

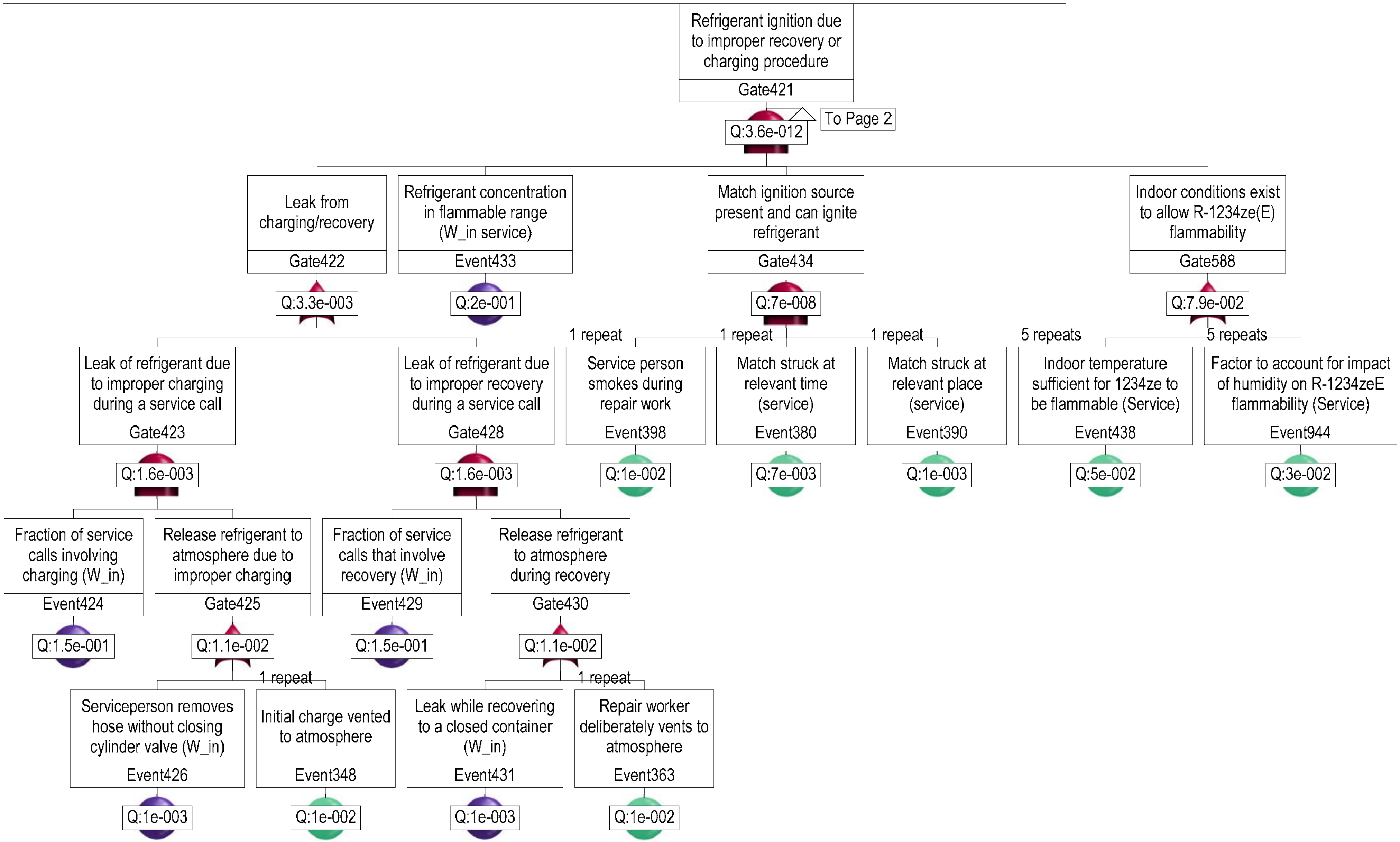

Ignition source present (R_in LgLk)
Gate225
Q:1.9e-003
To Page 1
Open flame present
Gate226
Q:1.9e-003
Sufficient electrical spark present
Gate232
Q:2.8e-011
Gas burner present
Gate227
Q:1.1e-003
Pilot light present
Gate578
Q:7.6e-004
9 repeats
Spark occurs
Event133
Q:7e-003
13 repeat
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (R_in LgLk kitchen)
Event218
Q:4e-003
13 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
3 repeats
Kitchen has gas burner
Event228
Q:9.5e-001
Gas flame present in flammable concentration area (R_in LgLk kitchen)
Event229
Q:2e-003
3 repeats
Gas flame present when flammable concentration present (kitchen)
Event806
Q:5.8e-001
Lighter/match flame present
Gate230
Q:1.5e-009
3 repeats
Kitchen has unshielded pilot light
Event893
Q:7.6e-001
Pilot light flame present in flammable concentration area (R_in LgLk, kitchen)
Event903
Q:1e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in LgLk kitchen)
Event231
Q:5e-004
3 repeats
Lighter/match flame present when flammable concentration present (kitchen)
Event833
Q:3e-004


R. Refrigerant ignition during servicing (risk per unit per year)
Gate322
Q:1.7e-013
Repair of reach in (R_in) unit
Gate323
Q:1.3e-014
Repair of walk in (W_in) unit
Gate407
Q:1.6e-013
From Page 2
Refrigerant ignition during service
Gate324
Q:1.3e-011
Probability reach in unit is serviced per year
Event406
Q:1e-003
Refrigerant ignition due to brazing of fitting indoors
Gate325
Q:5e-014
Refrigerant ignition by propane torch leak test
Gate391
Q:1.2e-012
1 repeat
Fraction of service calls involving brazing indoors (R_in)
Event336
Q:7.5e-003
Refrigerant concentration in flammable zone indoors
Gate337
Q:6.7e-008
Service person uses brazing torch at relevant time indoors
Event340
Q:1e-004
Refrigerant ignition due to improper recovery or charging procedure
Gate342
Q:1.2e-011
From Page 5
Use of propane torch to test for leak
Gate392
Q:5e-008
Fraction of service calls involving a moderate or large leak (R_in)
Event404
Q:1e-003
Service person recharges leak prior to looking for leak with flammable refrigerant
Event405
Q:3e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate589
Q:7.9e-002
1 repeat
Sufficient refrigerant involved (indoors)
Event338
Q:1e-006
No dispersion by indoor air currents (e.g., fan) during service (R_in)
Event339
Q:8.5e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate590
Q:7.9e-002
1 repeat
Service person routinely uses torch to test for a leak
Event1072
Q:5e-003
1 repeat
Serviceman believes refrigerant is non-flammable
Event402
Q:1e-004
1 repeat
Large leak is not detected by other means
Event403
Q:1e-001
5 repeats
Indoor temperature sufficient for 1234ze to be flammable (Service)
Event438
Q:5e-002
5 repeats
Factor to account for impact of humidity on R-1234zeE flammability (Service)
Event944
Q:3e-002
5 repeats
Indoor temperature sufficient for 1234ze to be flammable (Service)
Event438
Q:5e-002
5 repeats
Factor to account for impact of humidity on R-1234zeE flammability (Service)
Event944
Q:3e-002

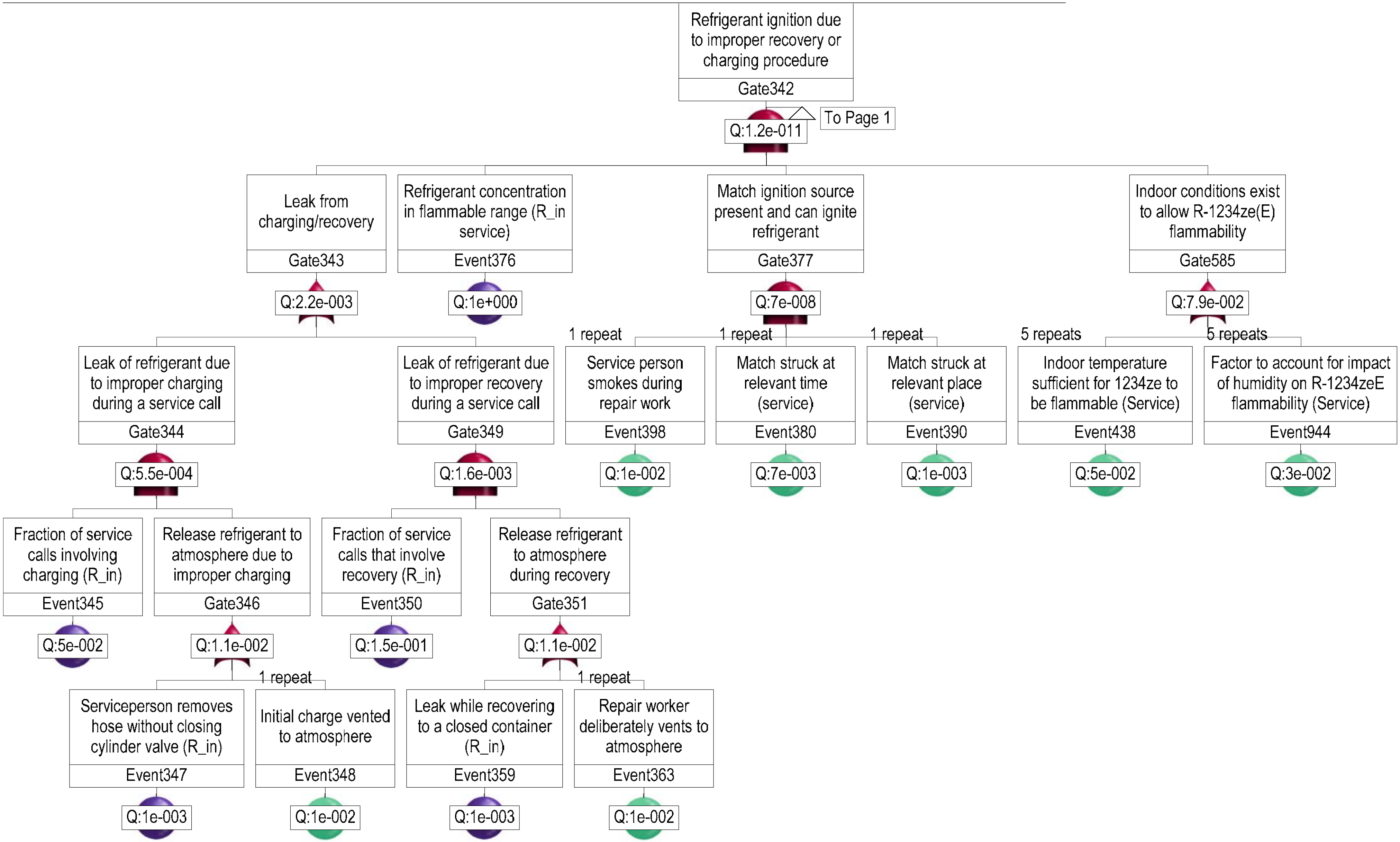


Repair of walk in (W_in) unit
Gate407
Q:1.6e-013
To Page 1
Refrigerant ignition during service
Gate408
Q:1.6e-011
Probability walk in unit is serviced per year
Event440
Q:1e-002
Refrigerant ignition due to brazing of fitting indoors
Gate409
Q:5e-013
Refrigerant ignition due to brazing of fitting outside
Gate415
Q:1.7e-013
From Page 3
Refrigerant ignition due to improper recovery or charging procedure
Gate421
Q:3.6e-012
From Page 4
Refrigerant ignition by propane torch leak test
Gate436
Q:1.2e-011
1 repeat
Fraction of service calls involving brazing indoors (W_in)
Event413
Q:7.5e-002
Service person uses brazing torch at relevant time indoors
Event340
Q:1e-004
Refrigerant concentration in flammable zone indoors
Gate410
Q:6.7e-008
Fraction of service calls involving a moderate or large leak (W_in)
Event437
Q:1e-002
1 repeat
Service person recharges leak prior to looking for leak with flammable refrigerant
Event405
Q:3e-001
Use of propane torch to test for leak
Gate439
Q:5e-008
1 repeat
Sufficient refrigerant involved (indoors)
Event338
Q:1e-006
No dispersion by indoor air currents (e.g., fan) (W_in)
Event412
Q:8.5e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate586
Q:7.9e-002
1 repeat
Service person routinely uses torch to test for a leak
Event1072
Q:5e-003
1 repeat
Serviceman believes refrigerant is non-flammable
Event402
Q:1e-004
1 repeat
Large leak is not detected by other means
Event403
Q:1e-001
Indoor conditions exist to allow R-1234ze(E) flammability
Gate587
Q:7.9e-002
5 repeats
Indoor temperature sufficient for 1234ze to be flammable (Service)
Event438
Q:5e-002
5 repeats
Factor to account for impact of humidity on R-1234zeE flammability (Service)
Event944
Q:3e-002
5 repeats
Indoor temperature sufficient for 1234ze to be flammable (Service)
Event438
Q:5e-002
5 repeats
Factor to account for impact of humidity on R-1234zeE flammability (Service)
Event944
Q:3e-002

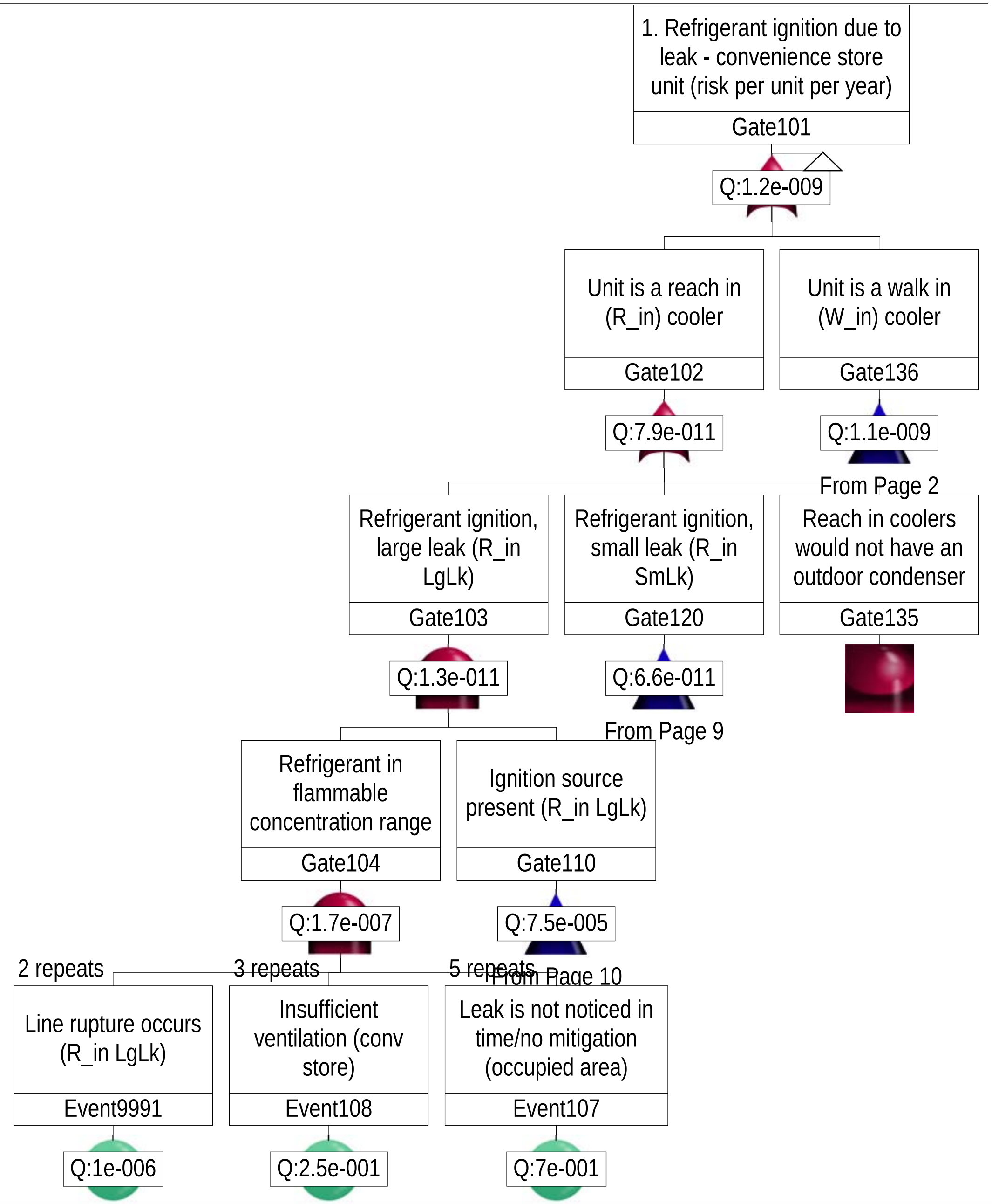

Refrigerant ignition due to brazing of fitting outside
Gate415
Q:1.7e-013
To Page 2
Fraction of service calls involving brazing outside (W_in)
Event416
Q:7.5e-002
Refrigerant concentration in flammable zone outside
Gate417
Q:6e-008
Service person uses brazing torch at relevant time outside
Event420
Q:1e-004
Outdoor conditions exist to allow R-1234ze(E) flammability
Gate661
Q:3.7e-001
10 repeat
6 repeats
6 repeats
Sufficient refrigerant involved (outside)
Event418
Q:1e-006
No wind
Event172
Q:6e-002
Outdoor temperature sufficient for 1234ze to be flammable
Event175
Q:3e-001
Factor to account for increased flammability at high humidity
Event1060
Q:1e-001

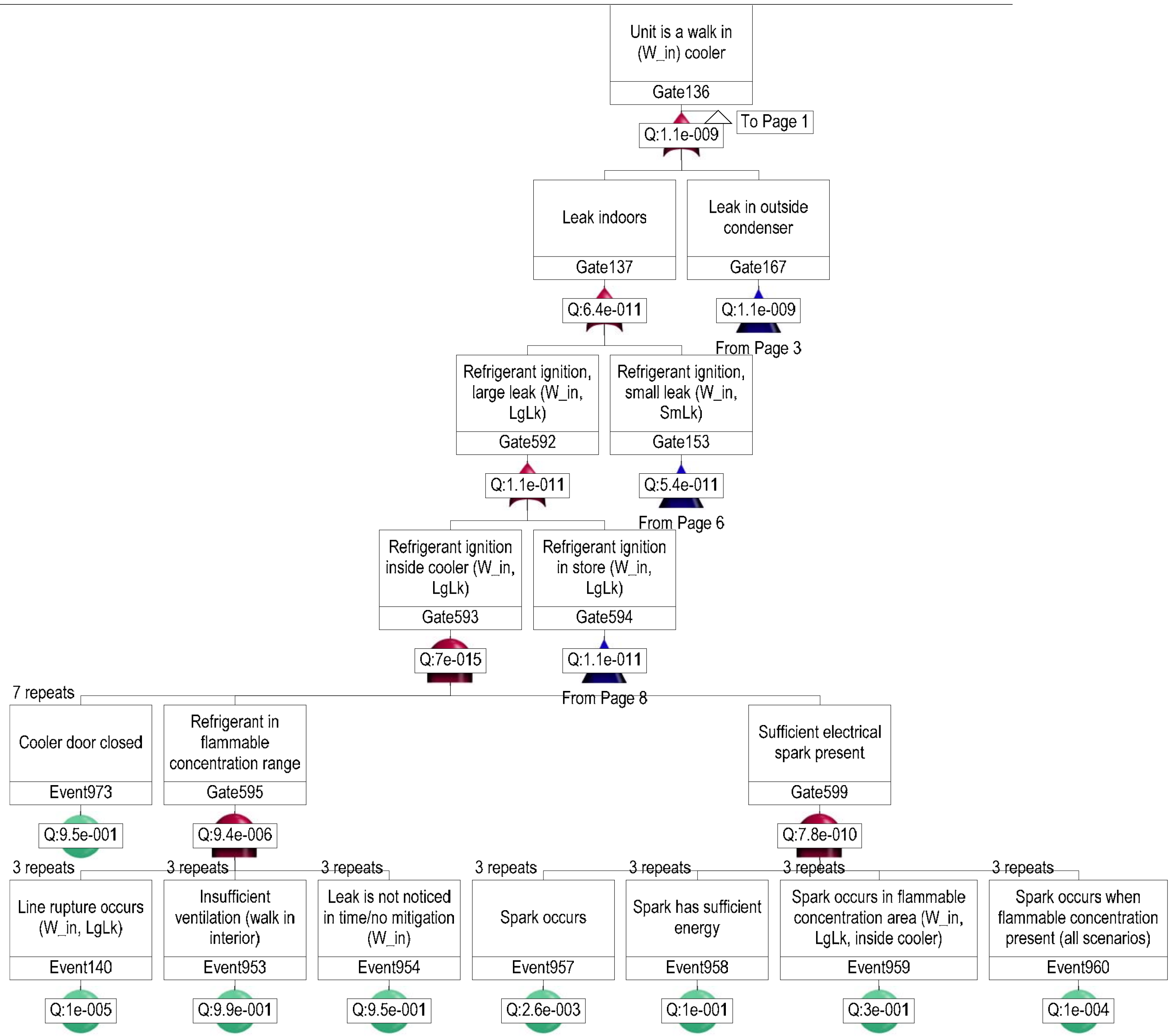


Refrigerant ignition due to improper recovery or charging procedure
Gate421
Q:3.6e-012
To Page 2
Leak from charging/recovery
Gate422
Q:3.3e-003
Refrigerant concentration in flammable range (W_in service)
Event433
Q:2e-001
Match ignition source present and can ignite refrigerant
Gate434
Q:7e-008
Indoor conditions exist to allow R-1234ze(E) flammability
Gate588
Q:7.9e-002
Leak of refrigerant due to improper charging during a service call
Gate423
Q:1.6e-003
Leak of refrigerant due to improper recovery during a service call
Gate428
Q:1.6e-003
1 repeat
Service person smokes during repair work
Event398
Q:1e-002
1 repeat
Match struck at relevant time (service)
Event380
Q:7e-003
1 repeat
Match struck at relevant place (service)
Event390
Q:1e-003
5 repeats
Indoor temperature sufficient for 1234ze to be flammable (Service)
Event438
Q:5e-002
5 repeats
Factor to account for impact of humidity on R-1234zeE flammability (Service)
Event944
Q:3e-002
Fraction of service calls involving charging (W_in)
Event424
Q:1.5e-001
Release refrigerant to atmosphere due to improper charging
Gate425
Q:1.1e-002
Fraction of service calls that involve recovery (W_in)
Event429
Q:1.5e-001
Release refrigerant to atmosphere during recovery
Gate430
Q:1.1e-002
Serviceperson removes hose without closing cylinder valve (W_in)
Event426
Q:1e-003
1 repeat
Initial charge vented to atmosphere
Event348
Q:1e-002
Leak while recovering to a closed container (W_in)
Event431
Q:1e-003
1 repeat
Repair worker deliberately vents to atmosphere
Event363
Q:1e-002

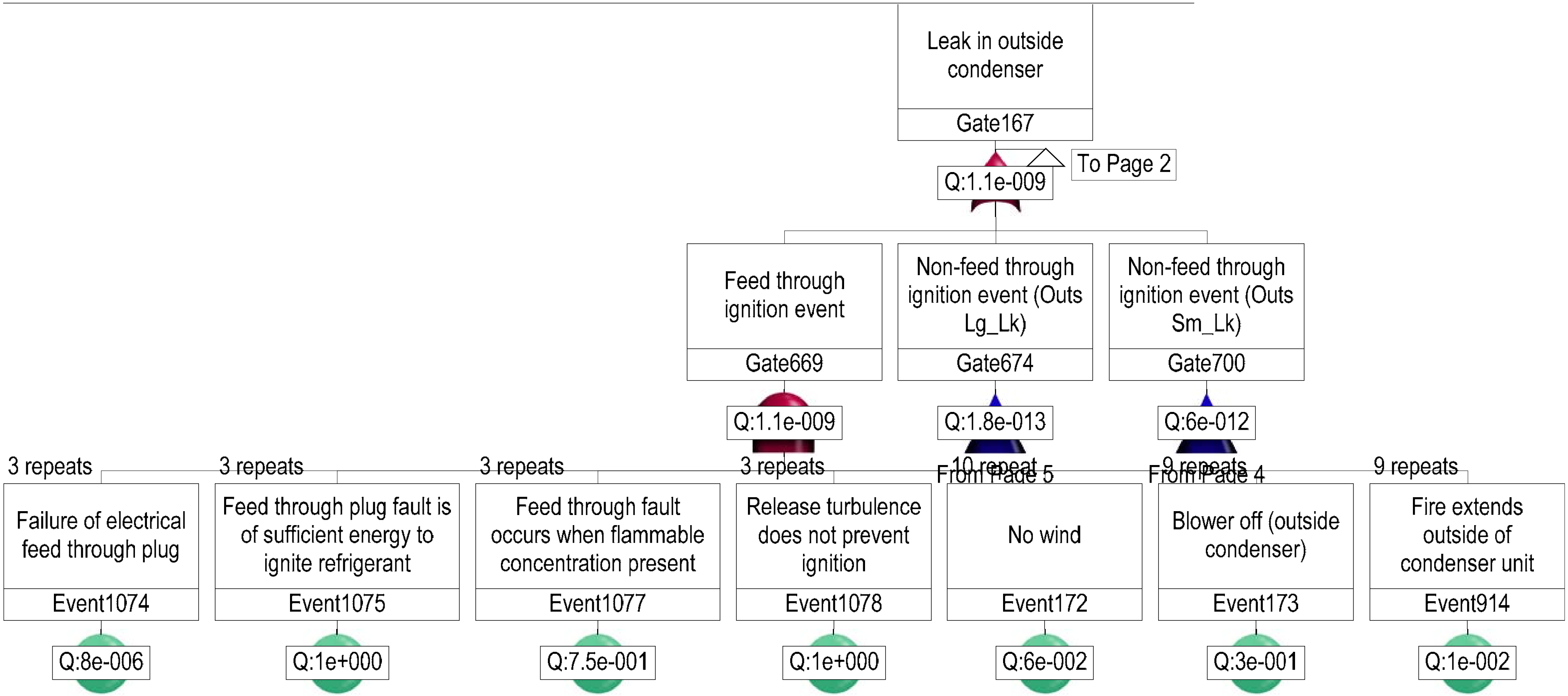

Refrigerant ignition due to improper recovery or charging procedure
Gate342
Q:1.2e-011
To Page 1
Leak from charging/recovery
Gate343
Q:2.2e-003
Refrigerant concentration in flammable range (R_in service)
Event376
Q:1e+000
Match ignition source present and can ignite refrigerant
Gate377
Q:7e-008
Indoor conditions exist to allow R-1234ze(E) flammability
Gate585
Q:7.9e-002
Leak of refrigerant due to improper charging during a service call
Gate344
Q:5.5e-004
Leak of refrigerant due to improper recovery during a service call
Gate349
Q:1.6e-003
1 repeat
Service person smokes during repair work
Event398
Q:1e-002
1 repeat
Match struck at relevant time (service)
Event380
Q:7e-003
1 repeat
Match struck at relevant place (service)
Event390
Q:1e-003
5 repeats
Indoor temperature sufficient for 1234ze to be flammable (Service)
Event438
Q:5e-002
5 repeats
Factor to account for impact of humidity on R-1234zeE flammability (Service)
Event944
Q:3e-002
Fraction of service calls involving charging (R_in)
Event345
Q:5e-002
Release refrigerant to atmosphere due to improper charging
Gate346
Q:1.1e-002
Fraction of service calls that involve recovery (R_in)
Event350
Q:1.5e-001
Release refrigerant to atmosphere during recovery
Gate351
Q:1.1e-002
Serviceperson removes hose without closing cylinder valve (R_in)
Event347
Q:1e-003
1 repeat
Initial charge vented to atmosphere
Event348
Q:1e-002
Leak while recovering to a closed container (R_in)
Event359
Q:1e-003
1 repeat
Repair worker deliberately vents to atmosphere
Event363
Q:1e-002

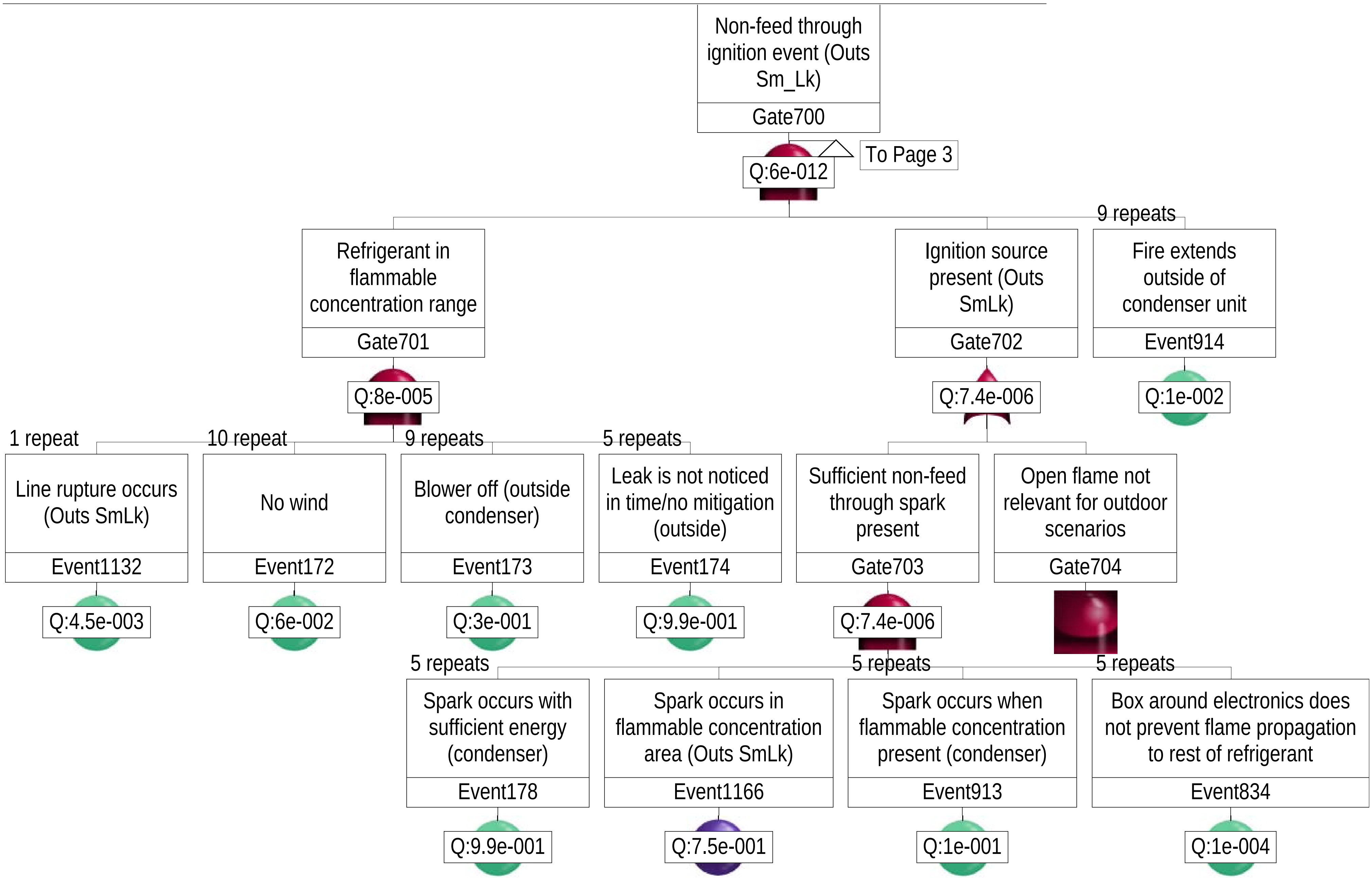
FAULT TREES FOR R-32

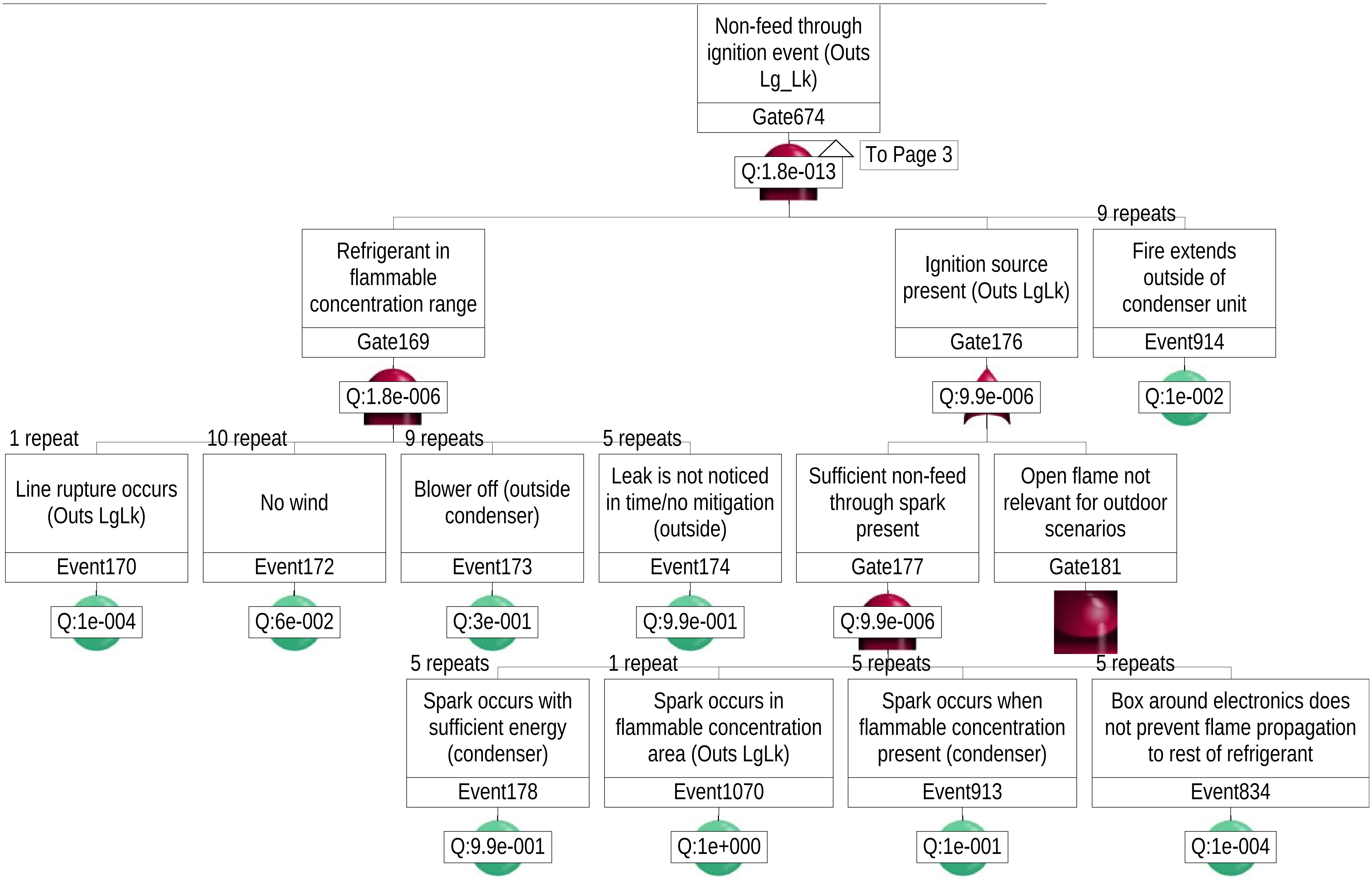

1. Refrigerant ignition due to leak - convenience store unit (risk per unit per year)
Gate101
Q:1.2e-009
Unit is a reach in (R_in) cooler
Gate102
Q:7.9e-011
Unit is a walk in (W_in) cooler
Gate136
Q:1.1e-009
From Page 2
Refrigerant ignition, large leak (R_in LgLk)
Gate103
Q:1.3e-011
Refrigerant ignition, small leak (R_in SmLk)
Gate120
Q:6.6e-011
From Page 9
Reach in coolers would not have an outdoor condenser
Gate135
Refrigerant in flammable concentration range
Gate104
Q:1.7e-007
Ignition source present (R_in LgLk)
Gate110
Q:7.5e-005
From Page 10
2 repeats
3 repeats
5 repeats
Line rupture occurs (R_in LgLk)
Event9991
Q:1e-006
Insufficient ventilation (conv store)
Event108
Q:2.5e-001
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001

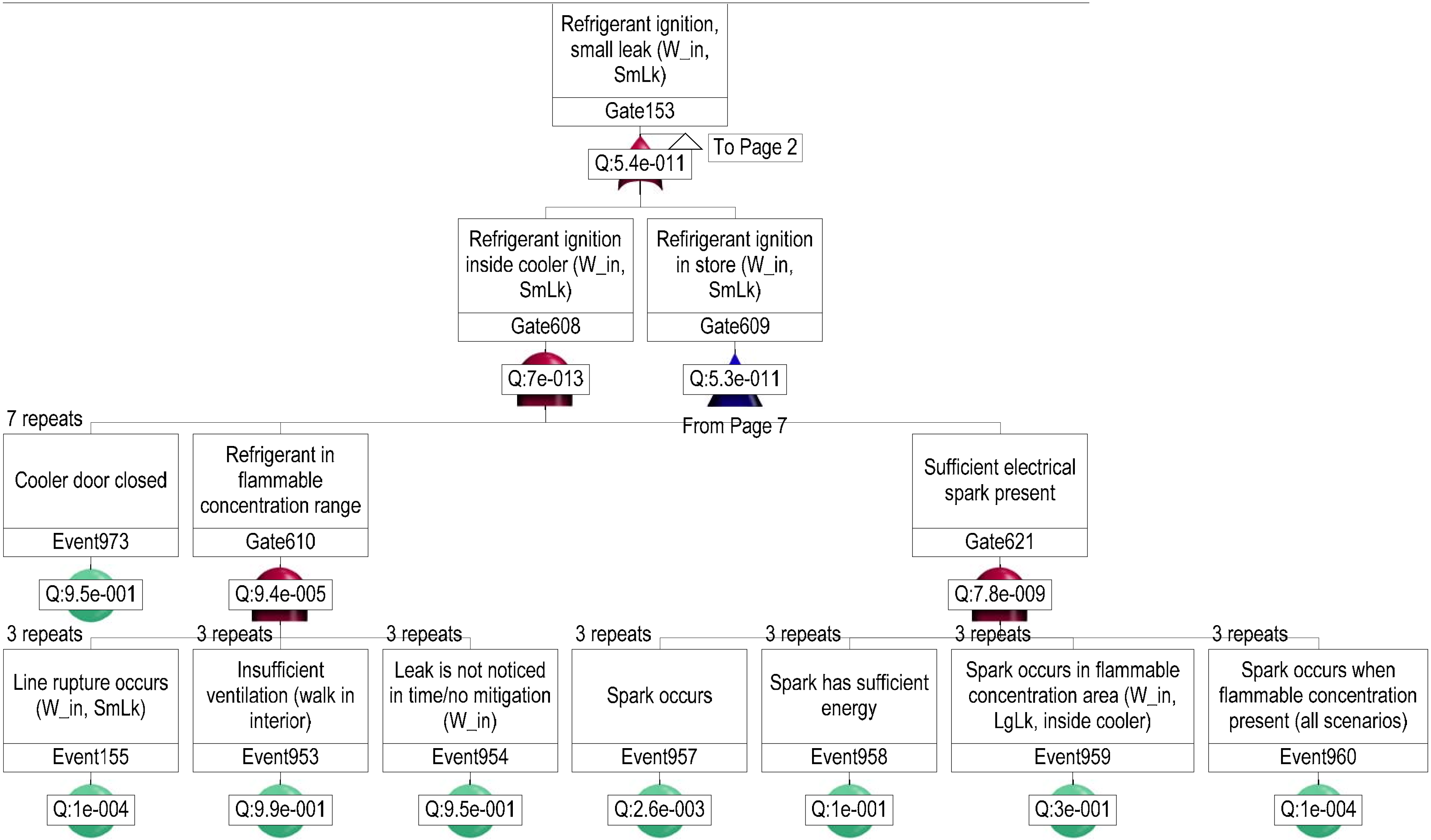

Unit is a walk in (W_in) cooler
Gate136
Q:1.1e-009
To Page 1
Leak indoors
Gate137
Q:6.4e-011
Leak in outside condenser
Gate167
Q:1.1e-009
From Page 3
Refrigerant ignition, large leak (W_in, LgLk)
Gate592
Q:1.1e-011
Refrigerant ignition, small leak (W_in, SmLk)
Gate153
Q:5.4e-011
From Page 6
Refrigerant ignition inside cooler (W_in, LgLk)
Gate593
Q:7e-015
Refrigerant ignition in store (W_in, LgLk)
Gate594
Q:1.1e-011
From Page 8
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Refrigerant in flammable concentration range
Gate595
Q:9.4e-006
Sufficient electrical spark present
Gate599
Q:7.8e-010
3 repeats
Line rupture occurs (W_in, LgLk)
Event140
Q:1e-005
3 repeats
Insufficient ventilation (walk in interior)
Event953
Q:9.9e-001
3 repeats
Leak is not noticed in time/no mitigation (W_in)
Event954
Q:9.5e-001
3 repeats
Spark occurs
Event957
Q:2.6e-003
3 repeats
Spark has sufficient energy
Event958
Q:1e-001
3 repeats
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)
Event959
Q:3e-001
3 repeats
Spark occurs when flammable concentration present (all scenarios)
Event960
Q:1e-004

GRADIENT


Leak in outside condenser
Gate167
Q:1.1e-009
To Page 2
Feed through ignition event
Gate669
Q:1.1e-009
Non-feed through ignition event (Outs Lg_Lk)
Gate674
Q:1.8e-013
From Page 5
Non-feed through ignition event (Outs Sm_Lk)
Gate700
Q:6e-012
From Page 4
3 repeats
Failure of electrical feed through plug
Event1074
Q:8e-006
3 repeats
Feed through plug fault is of sufficient energy to ignite refrigerant
Event1075
Q:1e+000
3 repeats
Feed through fault occurs when flammable concentration present
Event1077
Q:7.5e-001
3 repeats
Release turbulence does not prevent ignition
Event1078
Q:1e+000
10 repeat
No wind
Event172
Q:6e-002
9 repeats
Blower off (outside condenser)
Event173
Q:3e-001
9 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002

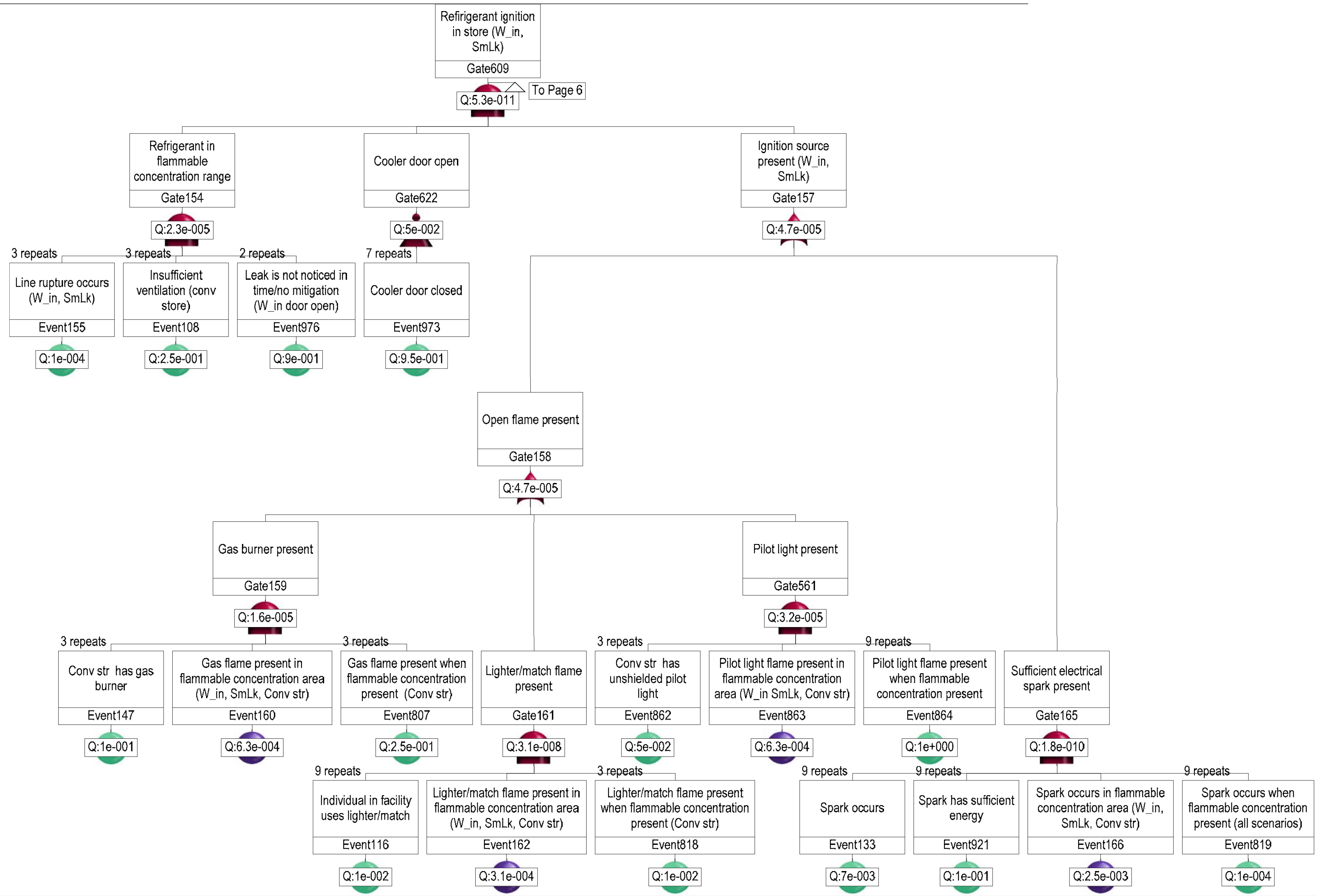

Non-feed through ignition event (Outs Sm_Lk)
Gate700
Q:6e-012
To Page 3
Refrigerant in flammable concentration range
Gate701
Q:8e-005
Ignition source present (Outs SmLk)
Gate702
Q:7.4e-006
9 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002
1 repeat
Line rupture occurs (Outs SmLk)
Event1132
Q:4.5e-003
10 repeat
No wind
Event172
Q:6e-002
9 repeats
Blower off (outside condenser)
Event173
Q:3e-001
5 repeats
Leak is not noticed in time/no mitigation (outside)
Event174
Q:9.9e-001
Sufficient non-feed through spark present
Gate703
Q:7.4e-006
Open flame not relevant for outdoor scenarios
Gate704
5 repeats
Spark occurs with sufficient energy (condenser)
Event178
Q:9.9e-001
Spark occurs in flammable concentration area (Outs SmLk)
Event1166
Q:7.5e-001
5 repeats
Spark occurs when flammable concentration present (condenser)
Event913
Q:1e-001
5 repeats
Box around electronics does not prevent flame propagation to rest of refrigerant
Event834
Q:1e-004

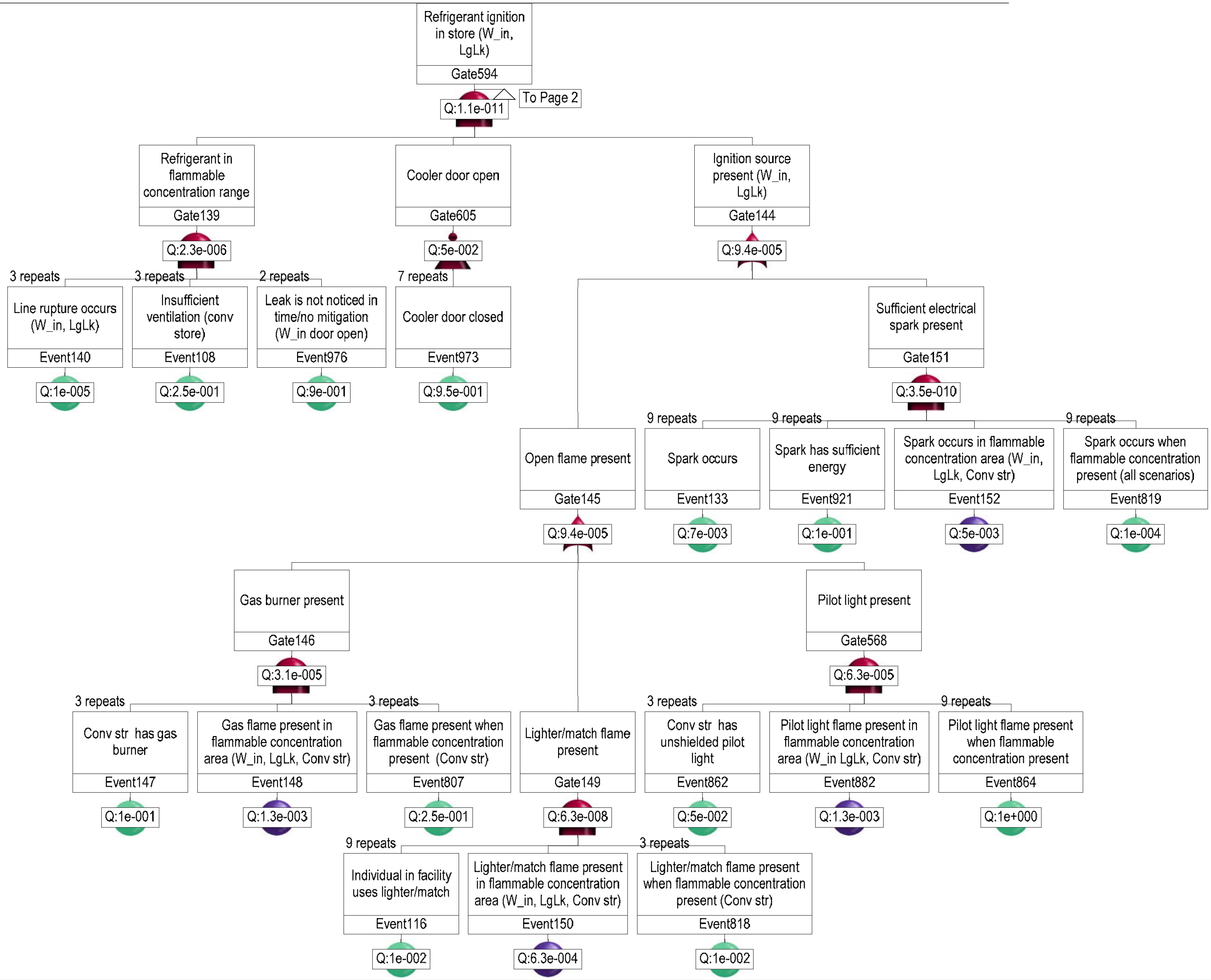

Non-feed through ignition event (Outs Lg_Lk)
Gate674
Q:1.8e-013
To Page 3
Refrigerant in flammable concentration range
Gate169
Q:1.8e-006
Ignition source present (Outs LgLk)
Gate176
Q:9.9e-006
9 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002
1 repeat
Line rupture occurs (Outs LgLk)
Event170
Q:1e-004
10 repeat
No wind
Event172
Q:6e-002
9 repeats
Blower off (outside condenser)
Event173
Q:3e-001
5 repeats
Leak is not noticed in time/no mitigation (outside)
Event174
Q:9.9e-001
Sufficient non-feed through spark present
Gate177
Q:9.9e-006
Open flame not relevant for outdoor scenarios
Gate181
5 repeats
Spark occurs with sufficient energy (condenser)
Event178
Q:9.9e-001
1 repeat
Spark occurs in flammable concentration area (Outs LgLk)
Event1070
Q:1e+000
5 repeats
Spark occurs when flammable concentration present (condenser)
Event913
Q:1e-001
5 repeats
Box around electronics does not prevent flame propagation to rest of refrigerant
Event834
Q:1e-004

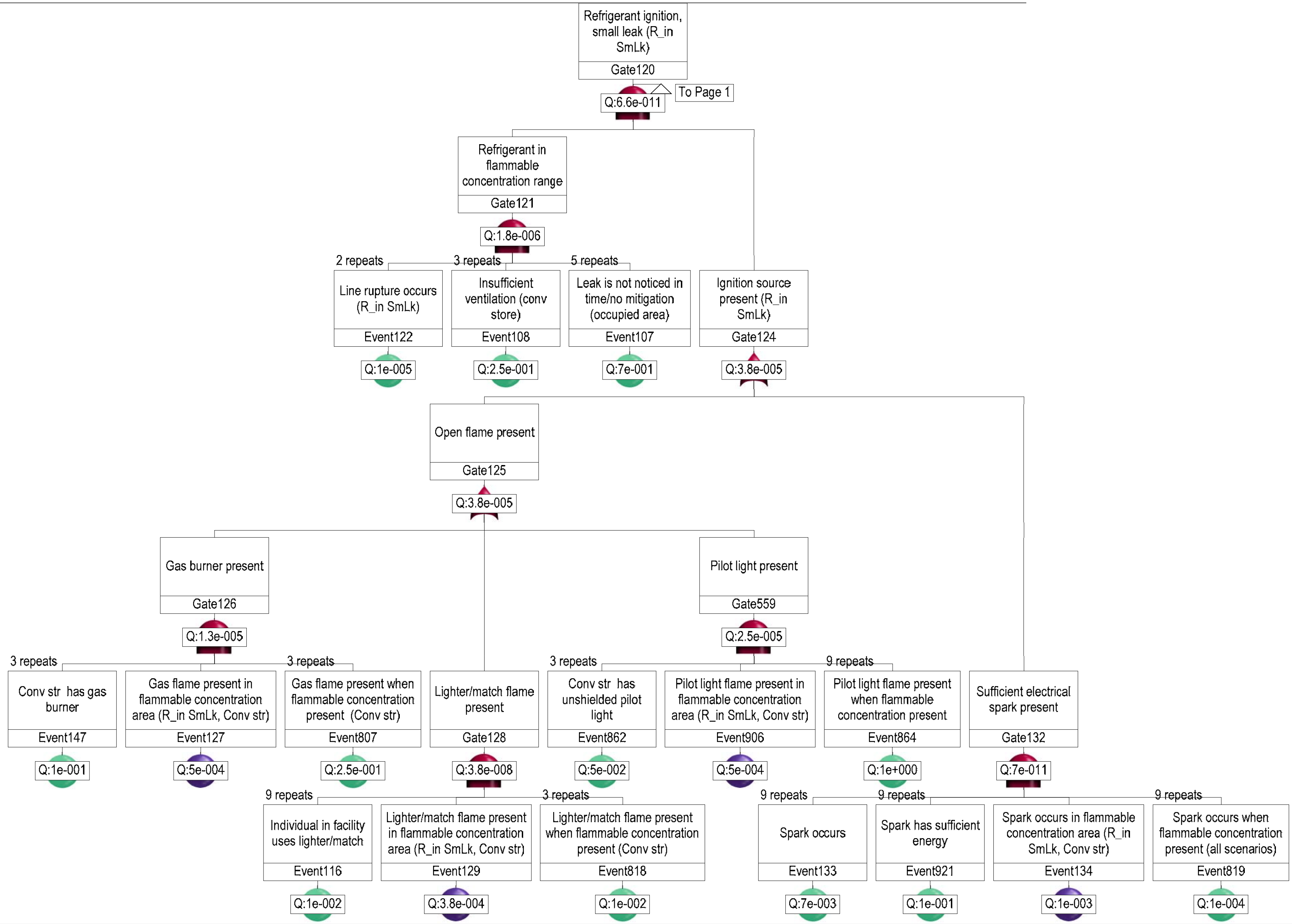


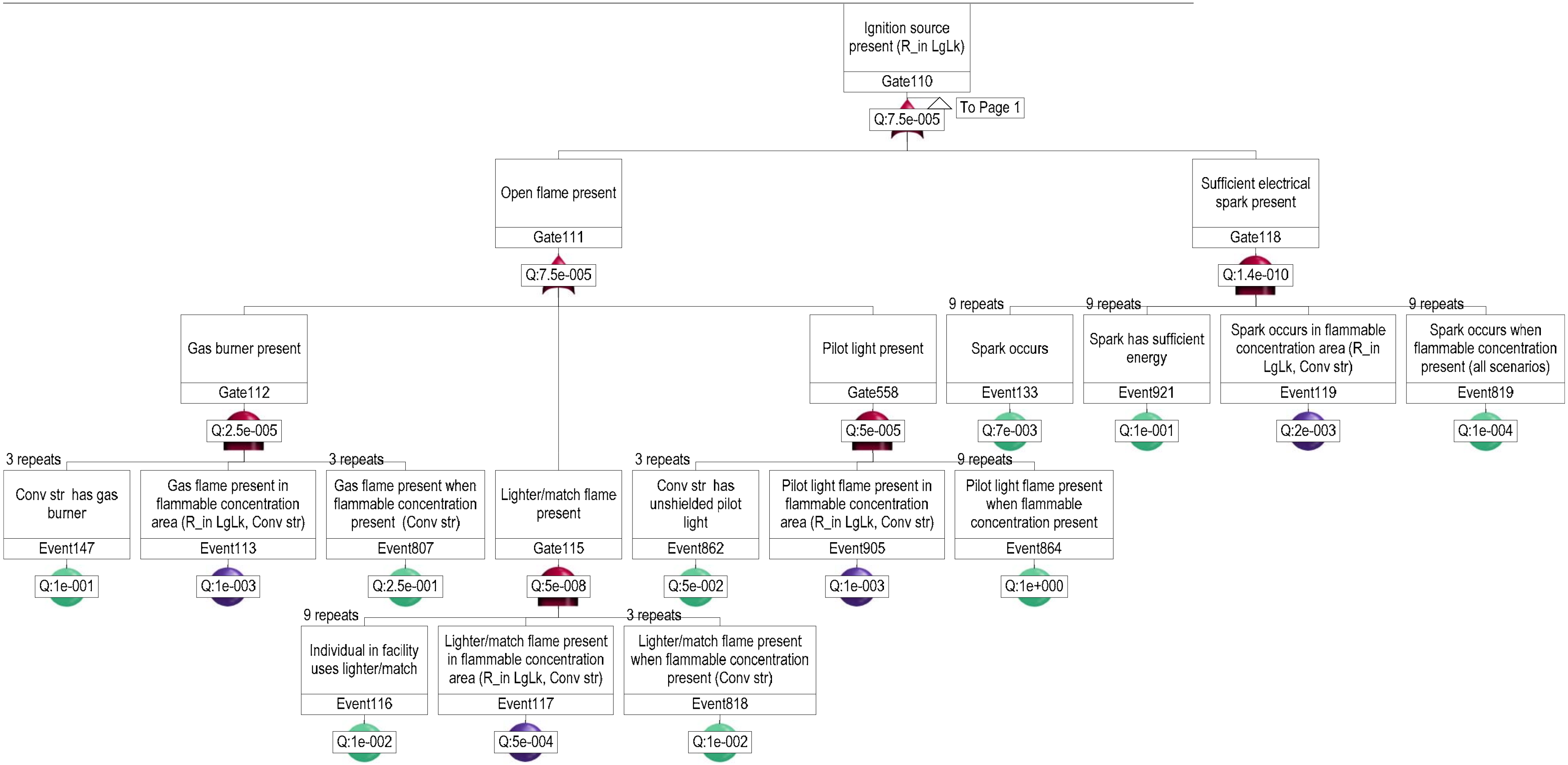
Refrigerant ignition, small leak (W_in, SmLk)
Gate153
Q:5.4e-011
To Page 2
Refrigerant ignition inside cooler (W_in, SmLk)
Gate608
Q:7e-013
Refrigerant ignition in store (W_in, SmLk)
Gate609
Q:5.3e-011
From Page 7
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Refrigerant in flammable concentration range
Gate610
Q:9.4e-005
Sufficient electrical spark present
Gate621
Q:7.8e-009
3 repeats
Line rupture occurs (W_in, SmLk)
Event155
Q:1e-004
3 repeats
Insufficient ventilation (walk in interior)
Event953
Q:9.9e-001
3 repeats
Leak is not noticed in time/no mitigation (W_in)
Event954
Q:9.5e-001
3 repeats
Spark occurs
Event957
Q:2.6e-003
3 repeats
Spark has sufficient energy
Event958
Q:1e-001
3 repeats
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)
Event959
Q:3e-001
3 repeats
Spark occurs when flammable concentration present (all scenarios)
Event960
Q:1e-004

GRADIENT

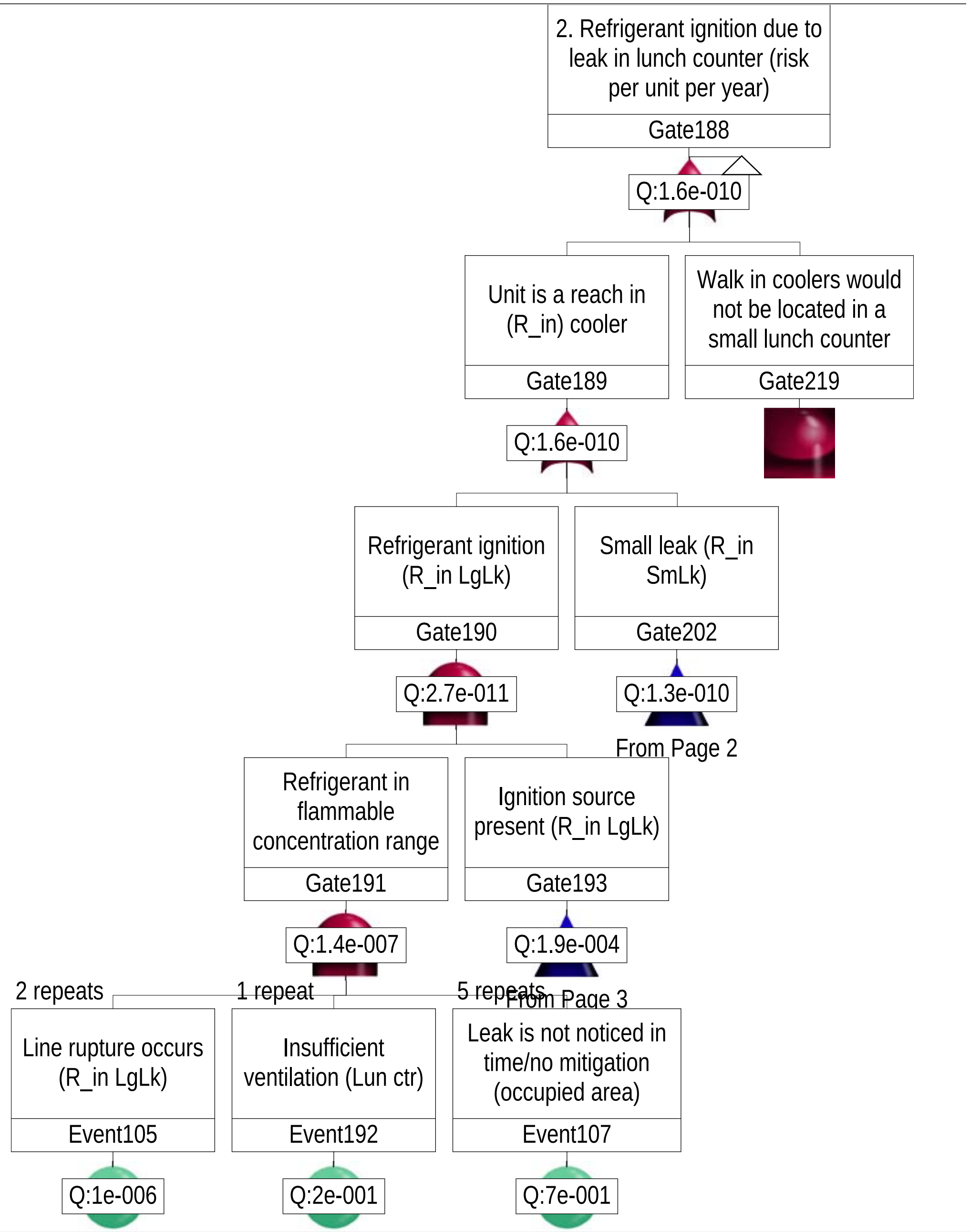

Refrigerant ignition in store (W_in, SmLk)
Gate609
Q:5.3e-011
To Page 6
Refrigerant in flammable concentration range
Gate154
Q:2.3e-005
Cooler door open
Gate622
Q:5e-002
Ignition source present (W_in, SmLk)
Gate157
Q:4.7e-005
3 repeats
Line rupture occurs (W_in, SmLk)
Event155
Q:1e-004
3 repeats
Insufficient ventilation (conv store)
Event108
Q:2.5e-001
2 repeats
Leak is not noticed in time/no mitigation (W_in door open)
Event976
Q:9e-001
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Open flame present
Gate158
Q:4.7e-005
Gas burner present
Gate159
Q:1.6e-005
Pilot light present
Gate561
Q:3.2e-005
3 repeats
Conv str has gas burner
Event147
Q:1e-001
Gas flame present in flammable concentration area (W_in, SmLk, Conv str)
Event160
Q:6.3e-004
3 repeats
Gas flame present when flammable concentration present (Conv str)
Event807
Q:2.5e-001
Lighter/match flame present
Gate161
Q:3.1e-008
3 repeats
Conv str has unshielded pilot light
Event862
Q:5e-002
Pilot light flame present in flammable concentration area (W_in SmLk, Conv str)
Event863
Q:6.3e-004
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
Sufficient electrical spark present
Gate165
Q:1.8e-010
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (W_in, SmLk, Conv str)
Event162
Q:3.1e-004
3 repeats
Lighter/match flame present when flammable concentration present (Conv str)
Event818
Q:1e-002
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-001
Spark occurs in flammable concentration area (W_in, SmLk, Conv str)
Event166
Q:2.5e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004

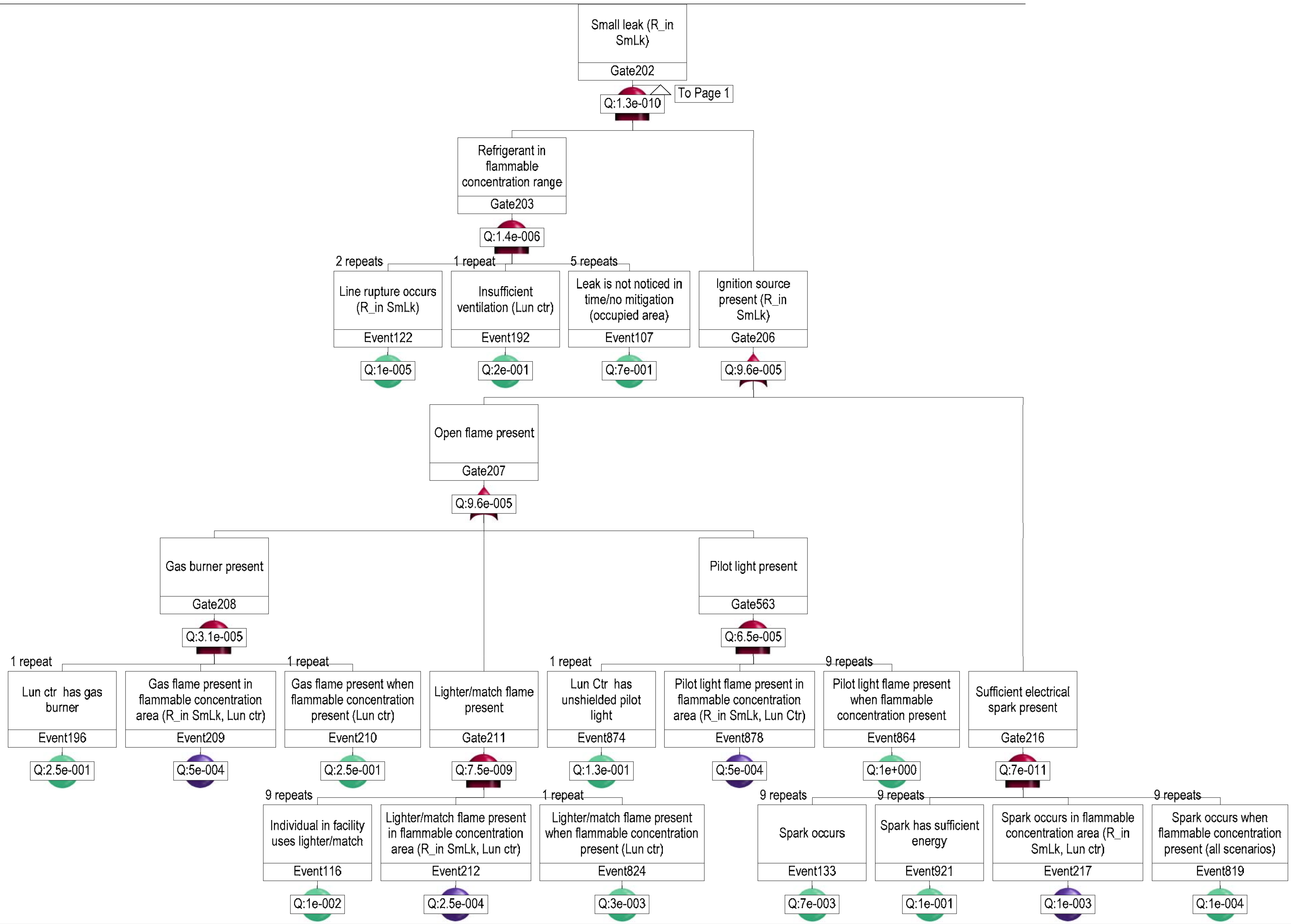

Refrigerant ignition in store (W_in, LgLk)
Gate594
Q:1.1e-011
To Page 2
Refrigerant in flammable concentration range
Gate139
Q:2.3e-006
Cooler door open
Gate605
Q:5e-002
Ignition source present (W_in, LgLk)
Gate144
Q:9.4e-005
3 repeats
Line rupture occurs (W_in, LgLk)
Event140
Q:1e-005
3 repeats
Insufficient ventilation (conv store)
Event108
Q:2.5e-001
2 repeats
Leak is not noticed in time/no mitigation (W_in door open)
Event976
Q:9e-001
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Sufficient electrical spark present
Gate151
Q:3.5e-010
Open flame present
Gate145
Q:9.4e-005
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-001
Spark occurs in flammable concentration area (W_in, LgLk, Conv str)
Event152
Q:5e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate146
Q:3.1e-005
Pilot light present
Gate568
Q:6.3e-005
3 repeats
Conv str has gas burner
Event147
Q:1e-001
Gas flame present in flammable concentration area (W_in, LgLk, Conv str)
Event148
Q:1.3e-003
3 repeats
Gas flame present when flammable concentration present (Conv str)
Event807
Q:2.5e-001
Lighter/match flame present
Gate149
Q:6.3e-008
3 repeats
Conv str has unshielded pilot light
Event862
Q:5e-002
Pilot light flame present in flammable concentration area (W_in LgLk, Conv str)
Event882
Q:1.3e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (W_in, LgLk, Conv str)
Event150
Q:6.3e-004
3 repeats
Lighter/match flame present when flammable concentration present (Conv str)
Event818
Q:1e-002

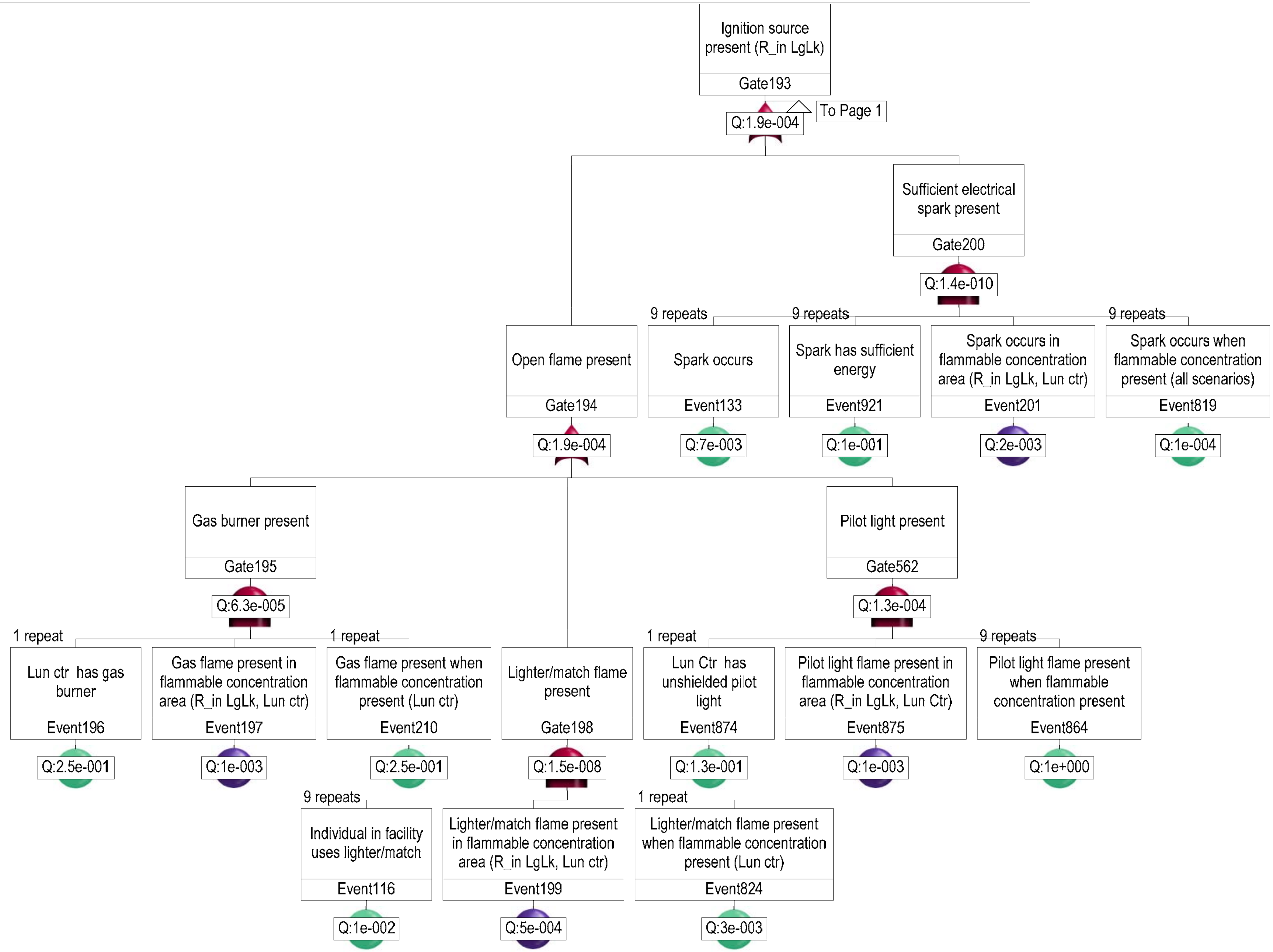

Refrigerant ignition, small leak (R_in SmLk)
Gate120
To Page 1
Q:6.6e-011
Refrigerant in flammable concentration range
Gate121
Q:1.8e-006
2 repeats
Line rupture occurs (R_in SmLk)
Event122
Q:1e-005
3 repeats
Insufficient ventilation (conv store)
Event108
Q:2.5e-001
5 repeats
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001
Ignition source present (R_in SmLk)
Gate124
Q:3.8e-005
Open flame present
Gate125
Q:3.8e-005
Gas burner present
Gate126
Q:1.3e-005
Pilot light present
Gate559
Q:2.5e-005
3 repeats
Conv str has gas burner
Event147
Q:1e-001
Gas flame present in flammable concentration area (R_in SmLk, Conv str)
Event127
Q:5e-004
3 repeats
Gas flame present when flammable concentration present (Conv str)
Event807
Q:2.5e-001
Lighter/match flame present
Gate128
Q:3.8e-008
3 repeats
Conv str has unshielded pilot light
Event862
Q:5e-002
Pilot light flame present in flammable concentration area (R_in SmLk, Conv str)
Event906
Q:5e-004
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
Sufficient electrical spark present
Gate132
Q:7e-011
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in SmLk, Conv str)
Event129
Q:3.8e-004
3 repeats
Lighter/match flame present when flammable concentration present (Conv str)
Event818
Q:1e-002
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-001
Spark occurs in flammable concentration area (R_in SmLk, Conv str)
Event134
Q:1e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004

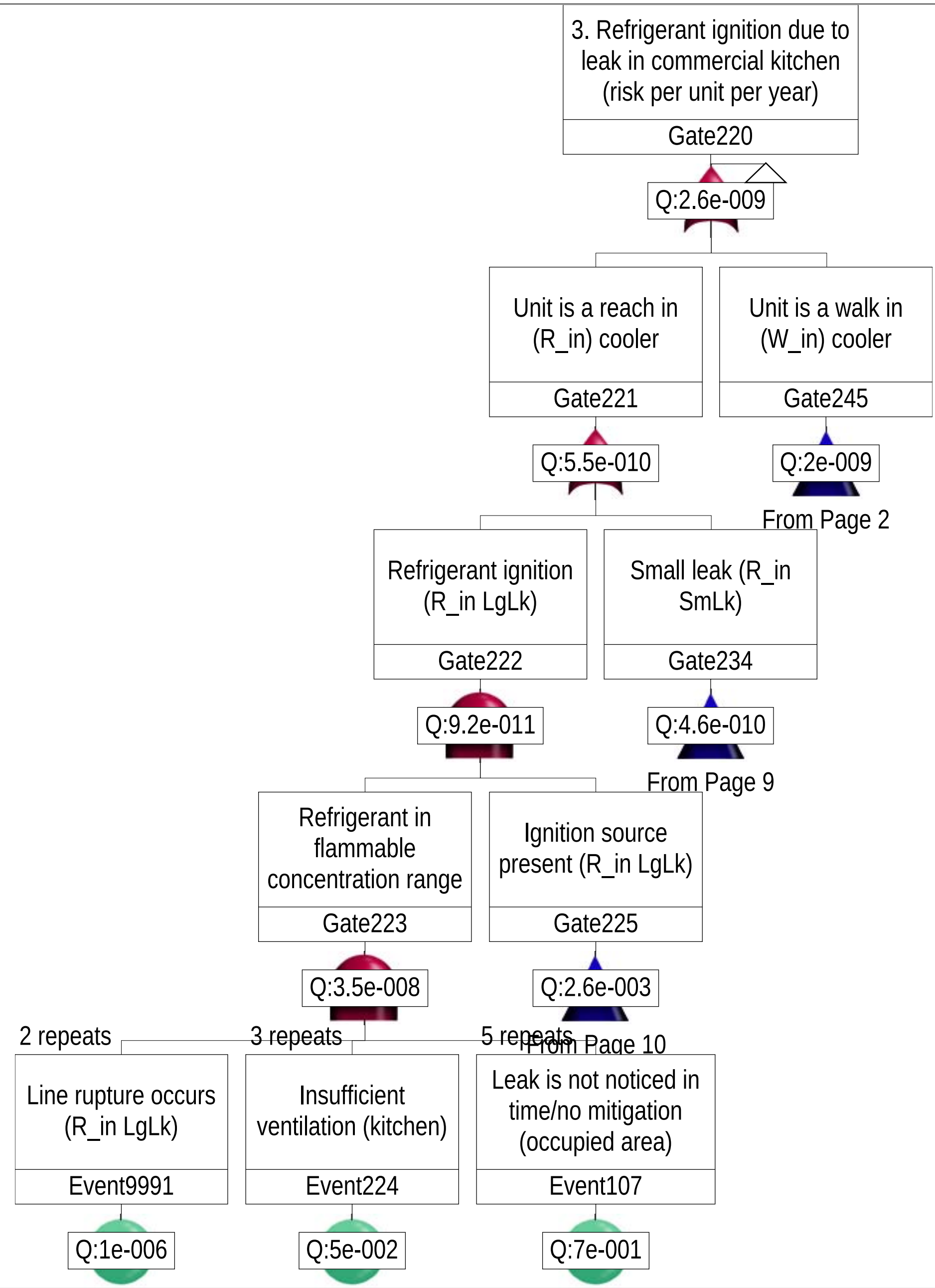


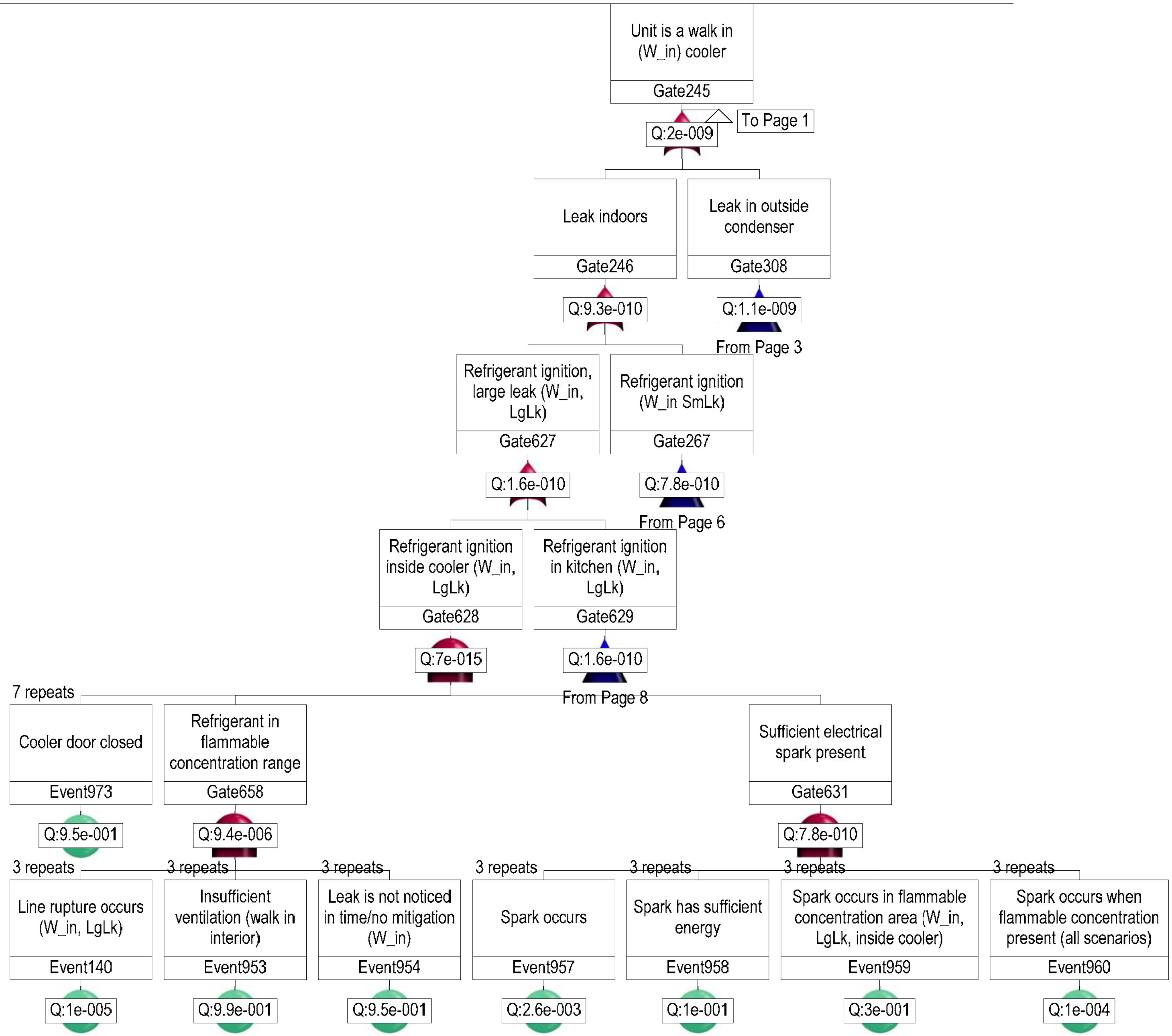
Ignition source present (R_in LgLk)
Gate110
Q:7.5e-005
To Page 1
Open flame present
Gate111
Q:7.5e-005
Sufficient electrical spark present
Gate118
Q:1.4e-010
Gas burner present
Gate112
Q:2.5e-005
Pilot light present
Gate558
Q:5e-005
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-001
Spark occurs in flammable concentration area (R_in LgLk, Conv str)
Event119
Q:2e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
3 repeats
Conv str has gas burner
Event147
Q:1e-001
Gas flame present in flammable concentration area (R_in LgLk, Conv str)
Event113
Q:1e-003
3 repeats
Gas flame present when flammable concentration present (Conv str)
Event807
Q:2.5e-001
Lighter/match flame present
Gate115
Q:5e-008
3 repeats
Conv str has unshielded pilot light
Event862
Q:5e-002
Pilot light flame present in flammable concentration area (R_in LgLk, Conv str)
Event905
Q:1e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in LgLk, Conv str)
Event117
Q:5e-004
3 repeats
Lighter/match flame present when flammable concentration present (Conv str)
Event818
Q:1e-002


2. Refrigerant ignition due to leak in lunch counter (risk per unit per year)
Gate188
Q:1.6e-010
Unit is a reach in (R_in) cooler
Gate189
Walk in coolers would not be located in a small lunch counter
Gate219
Q:1.6e-010
Refrigerant ignition (R_in LgLk)
Gate190
Small leak (R_in SmLk)
Gate202
Q:2.7e-011
Q:1.3e-010
From Page 2
Refrigerant in flammable concentration range
Gate191
Ignition source present (R_in LgLk)
Gate193
Q:1.4e-007
Q:1.9e-004
From Page 3
2 repeats
1 repeat
5 repeats
Line rupture occurs (R_in LgLk)
Event105
Insufficient ventilation (Lun ctr)
Event192
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:1e-006
Q:2e-001
Q:7e-001


Small leak (R_in SmLk)
Gate202
To Page 1
Q:1.3e-010
Refrigerant in flammable concentration range
Gate203
Q:1.4e-006
2 repeats
1 repeat
5 repeats
Line rupture occurs (R_in SmLk)
Event122
Q:1e-005
Insufficient ventilation (Lun ctr)
Event192
Q:2e-001
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001
Ignition source present (R_in SmLk)
Gate206
Q:9.6e-005
Open flame present
Gate207
Q:9.6e-005
Gas burner present
Gate208
Q:3.1e-005
Pilot light present
Gate563
Q:6.5e-005
1 repeat
Lun ctr has gas burner
Event196
Q:2.5e-001
Gas flame present in flammable concentration area (R_in SmLk, Lun ctr)
Event209
Q:5e-004
1 repeat
Gas flame present when flammable concentration present (Lun ctr)
Event210
Q:2.5e-001
Lighter/match flame present
Gate211
Q:7.5e-009
1 repeat
Lun Ctr has unshielded pilot light
Event874
Q:1.3e-001
Pilot light flame present in flammable concentration area (R_in SmLk, Lun Ctr)
Event878
Q:5e-004
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
Sufficient electrical spark present
Gate216
Q:7e-011
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in SmLk, Lun ctr)
Event212
Q:2.5e-004
1 repeat
Lighter/match flame present when flammable concentration present (Lun ctr)
Event824
Q:3e-003
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-001
Spark occurs in flammable concentration area (R_in SmLk, Lun ctr)
Event217
Q:1e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004

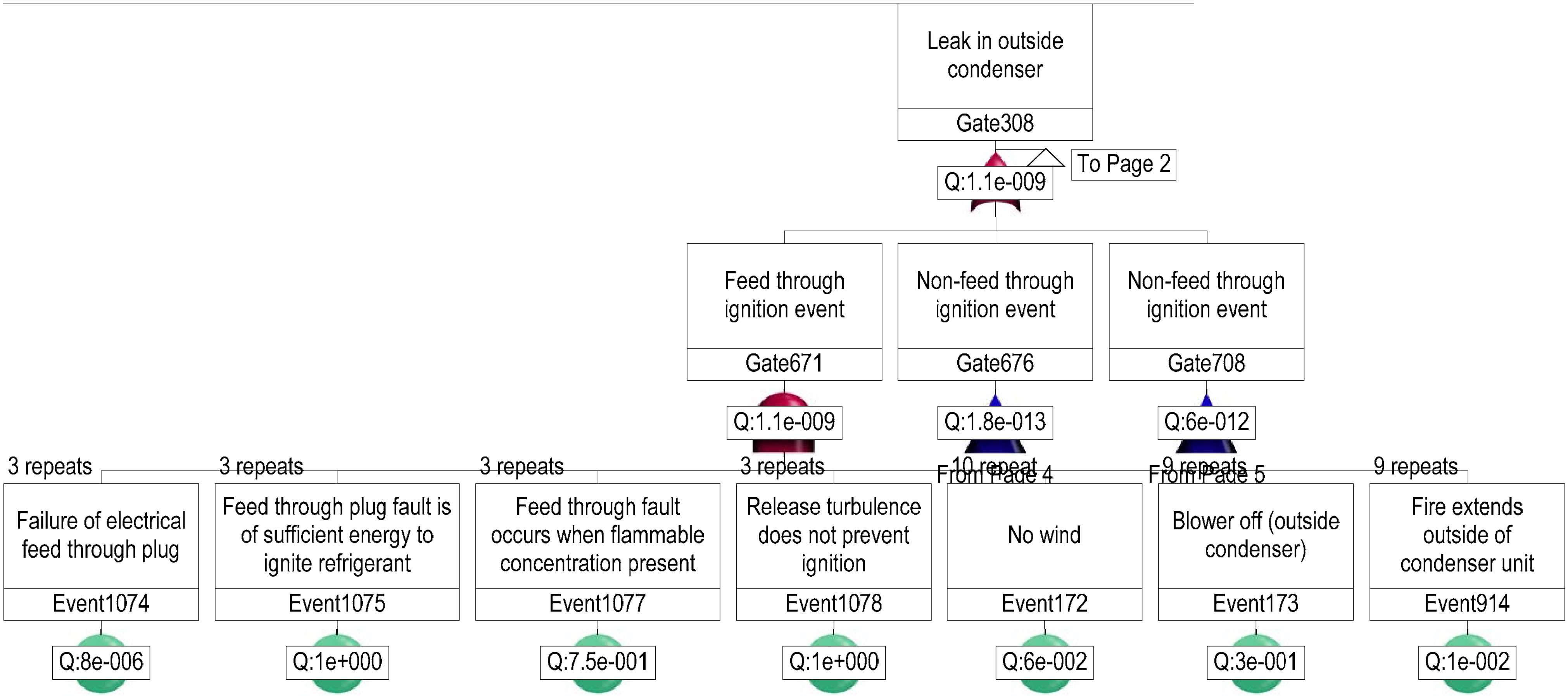

Ignition source present (R_in LgLk)
Gate193
Q:1.9e-004
To Page 1
Sufficient electrical spark present
Gate200
Q:1.4e-010
9 repeats
9 repeats
9 repeats
Open flame present
Gate194
Q:1.9e-004
Spark occurs
Event133
Q:7e-003
Spark has sufficient energy
Event921
Q:1e-001
Spark occurs in flammable concentration area (R_in LgLk, Lun ctr)
Event201
Q:2e-003
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate195
Q:6.3e-005
Pilot light present
Gate562
Q:1.3e-004
1 repeat
1 repeat
1 repeat
9 repeats
Lun ctr has gas burner
Event196
Q:2.5e-001
Gas flame present in flammable concentration area (R_in LgLk, Lun ctr)
Event197
Q:1e-003
Gas flame present when flammable concentration present (Lun ctr)
Event210
Q:2.5e-001
Lighter/match flame present
Gate198
Q:1.5e-008
Lun Ctr has unshielded pilot light
Event874
Q:1.3e-001
Pilot light flame present in flammable concentration area (R_in LgLk, Lun Ctr)
Event875
Q:1e-003
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
1 repeat
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in LgLk, Lun ctr)
Event199
Q:5e-004
Lighter/match flame present when flammable concentration present (Lun ctr)
Event824
Q:3e-003

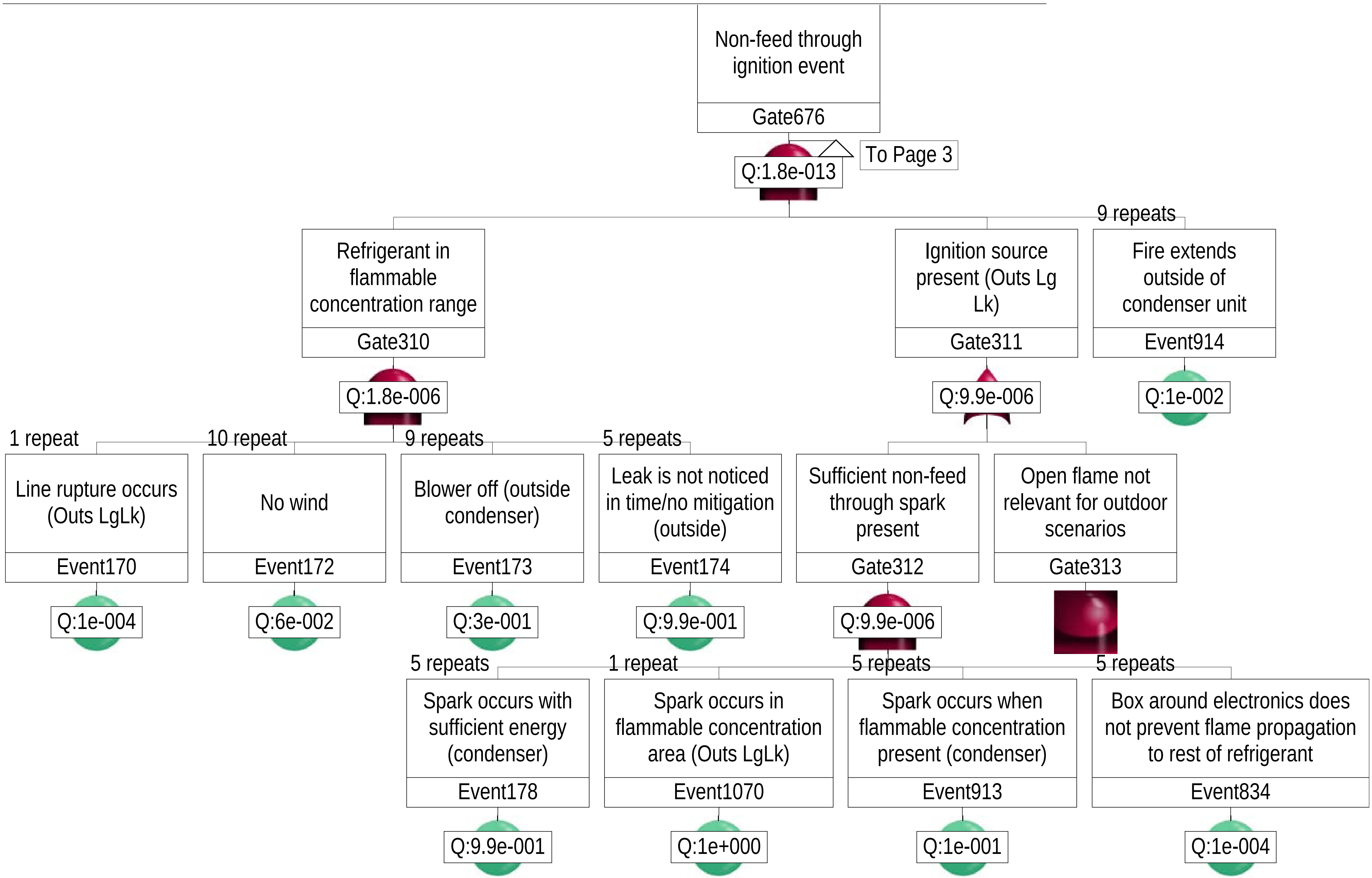

3. Refrigerant ignition due to leak in commercial kitchen (risk per unit per year)
Gate220
Q:2.6e-009
Unit is a reach in (R_in) cooler
Gate221
Q:5.5e-010
Unit is a walk in (W_in) cooler
Gate245
Q:2e-009
From Page 2
Refrigerant ignition (R_in LgLk)
Gate222
Q:9.2e-011
Small leak (R_in SmLk)
Gate234
Q:4.6e-010
From Page 9
Refrigerant in flammable concentration range
Gate223
Q:3.5e-008
Ignition source present (R_in LgLk)
Gate225
Q:2.6e-003
From Page 10
2 repeats
3 repeats
5 repeats
Line rupture occurs (R_in LgLk)
Event9991
Q:1e-006
Insufficient ventilation (kitchen)
Event224
Q:5e-002
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001

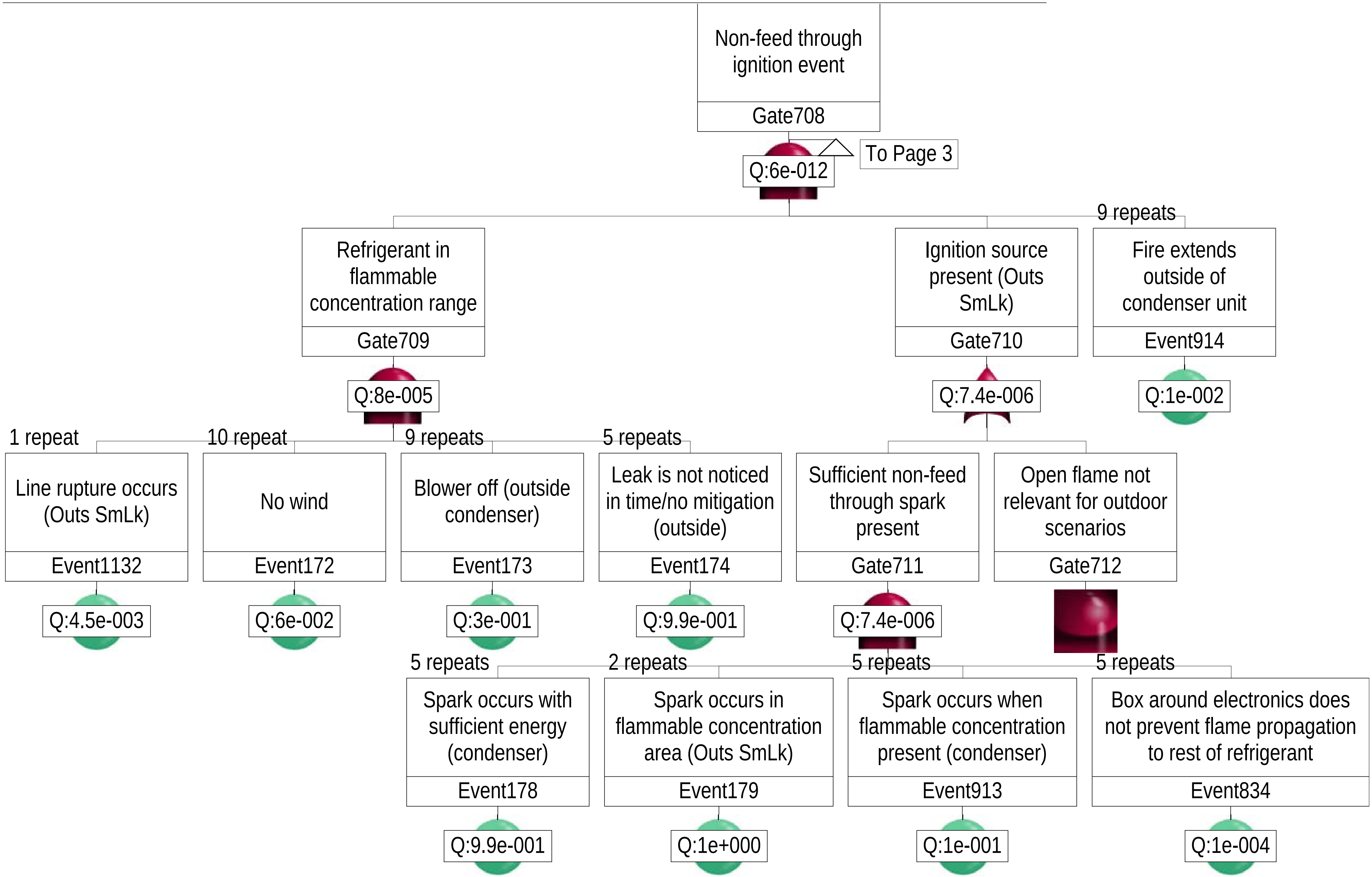


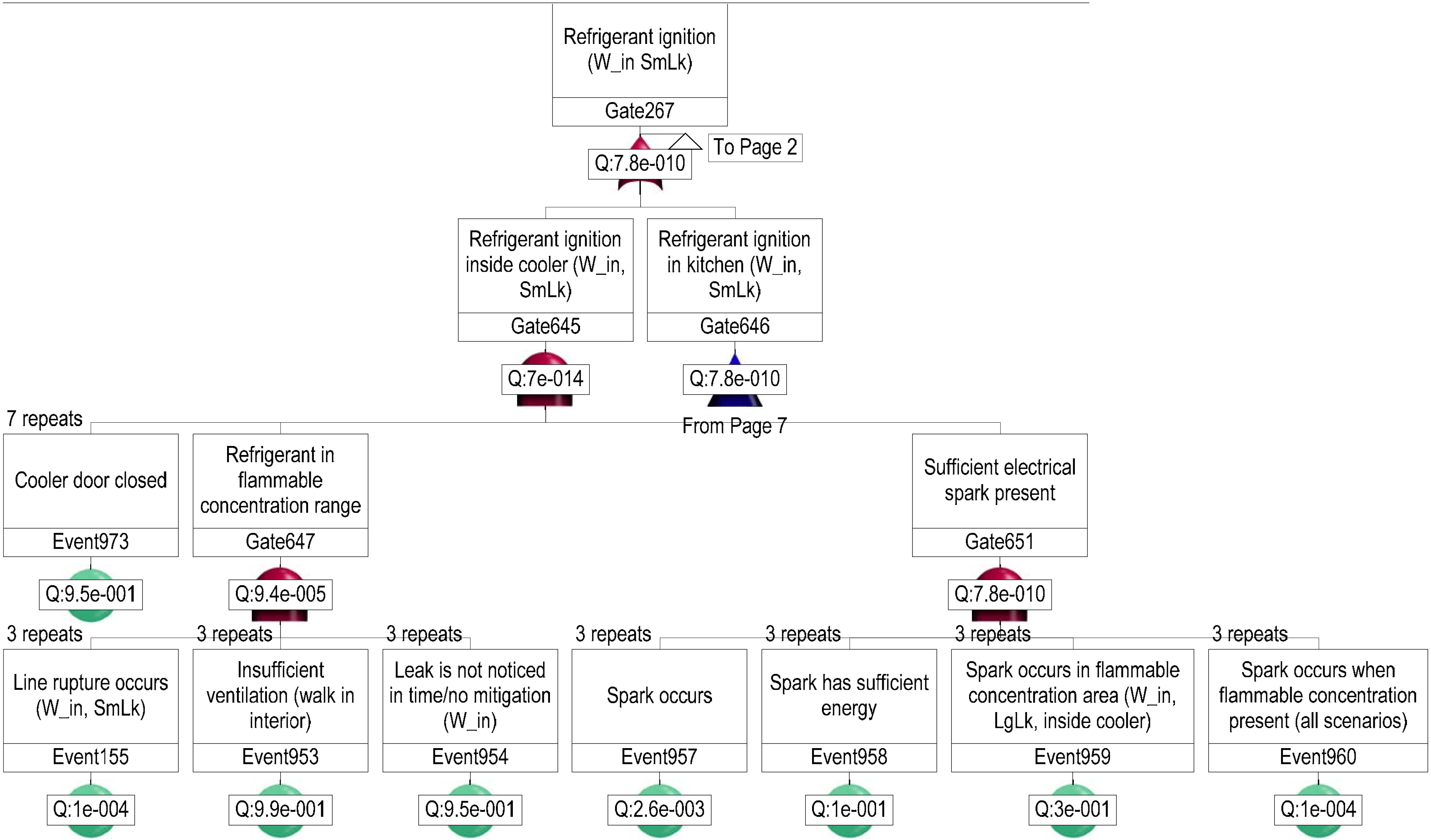
Unit is a walk in (W_in) cooler
Gate245
Q:2e-009
To Page 1
Leak indoors
Gate246
Q:9.3e-010
Leak in outside condenser
Gate308
Q:1.1e-009
From Page 3
Refrigerant ignition, large leak (W_in, LgLk)
Gate627
Q:1.6e-010
Refrigerant ignition (W_in SmLk)
Gate267
Q:7.8e-010
From Page 6
Refrigerant ignition inside cooler (W_in, LgLk)
Gate628
Q:7e-015
Refrigerant ignition in kitchen (W_in, LgLk)
Gate629
Q:1.6e-010
From Page 8
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Refrigerant in flammable concentration range
Gate658
Q:9.4e-006
Sufficient electrical spark present
Gate631
Q:7.8e-010
3 repeats
Line rupture occurs (W_in, LgLk)
Event140
Q:1e-005
3 repeats
Insufficient ventilation (walk in interior)
Event953
Q:9.9e-001
3 repeats
Leak is not noticed in time/no mitigation (W_in)
Event954
Q:9.5e-001
3 repeats
Spark occurs
Event957
Q:2.6e-003
3 repeats
Spark has sufficient energy
Event958
Q:1e-001
3 repeats
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)
Event959
Q:3e-001
3 repeats
Spark occurs when flammable concentration present (all scenarios)
Event960
Q:1e-004

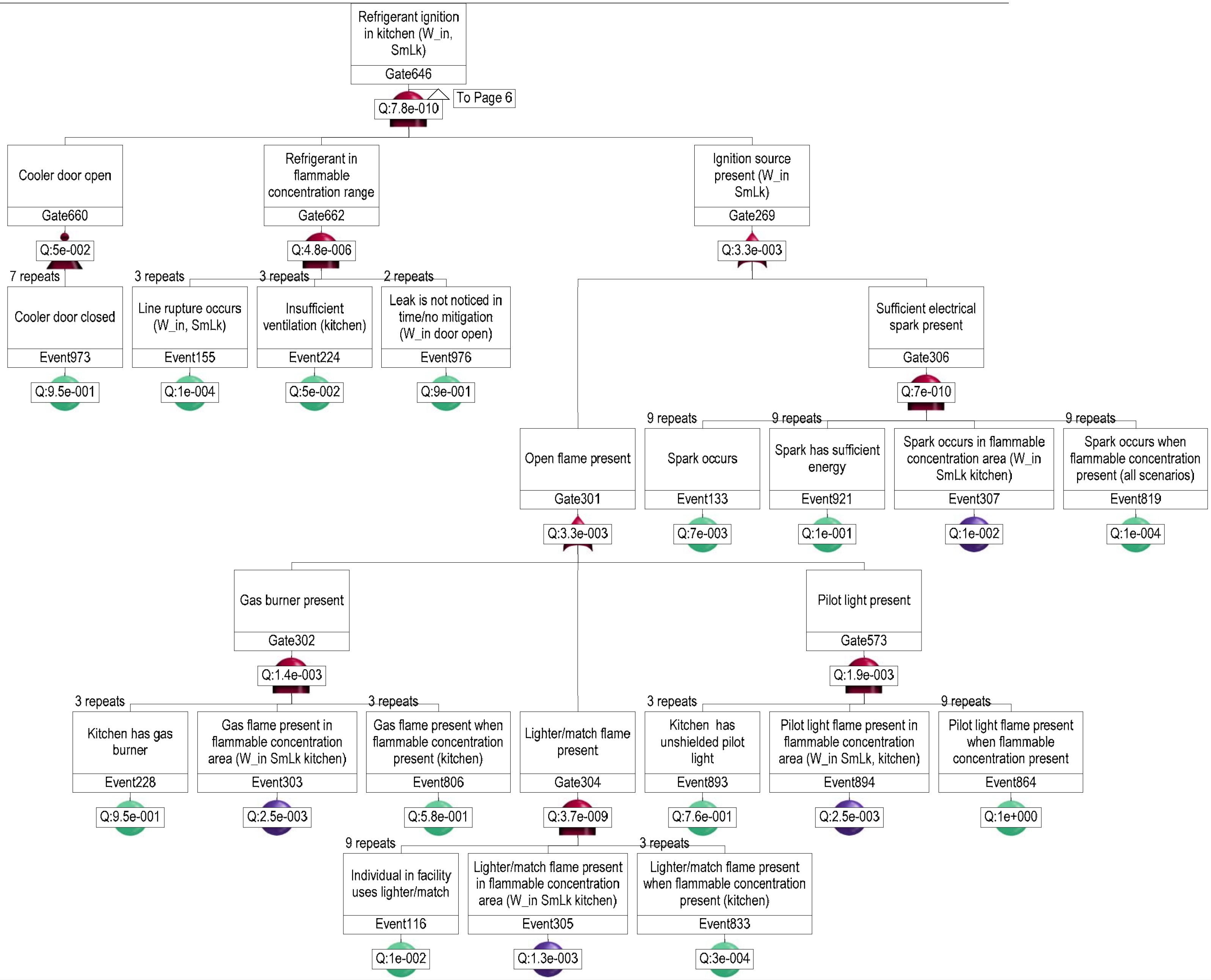
GRADIENT


Leak in outside condenser
Gate308
Q:1.1e-009
To Page 2
Feed through ignition event
Gate671
Q:1.1e-009
Non-feed through ignition event
Gate676
Q:1.8e-013
From Page 4
Non-feed through ignition event
Gate708
Q:6e-012
From Page 5
3 repeats
Failure of electrical feed through plug
Event1074
Q:8e-006
3 repeats
Feed through plug fault is of sufficient energy to ignite refrigerant
Event1075
Q:1e+000
3 repeats
Feed through fault occurs when flammable concentration present
Event1077
Q:7.5e-001
3 repeats
Release turbulence does not prevent ignition
Event1078
Q:1e+000
10 repeat
No wind
Event172
Q:6e-002
9 repeats
Blower off (outside condenser)
Event173
Q:3e-001
9 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002

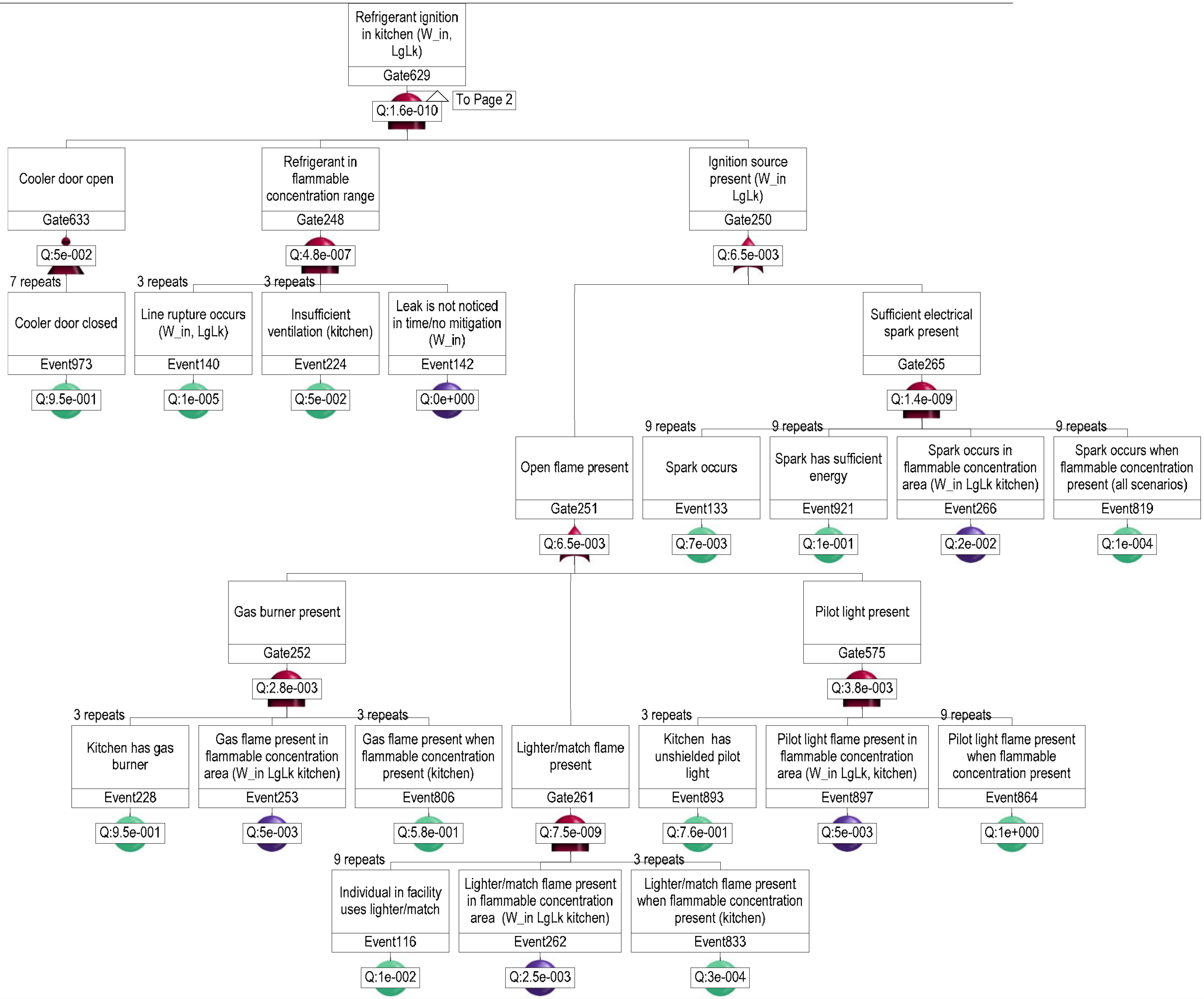

Non-feed through ignition event
Gate676
Q:1.8e-013
To Page 3
Refrigerant in flammable concentration range
Gate310
Q:1.8e-006
Ignition source present (Outs Lg Lk)
Gate311
Q:9.9e-006
9 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002
1 repeat
Line rupture occurs (Outs LgLk)
Event170
Q:1e-004
10 repeat
No wind
Event172
Q:6e-002
9 repeats
Blower off (outside condenser)
Event173
Q:3e-001
5 repeats
Leak is not noticed in time/no mitigation (outside)
Event174
Q:9.9e-001
Sufficient non-feed through spark present
Gate312
Q:9.9e-006
Open flame not relevant for outdoor scenarios
Gate313
5 repeats
Spark occurs with sufficient energy (condenser)
Event178
Q:9.9e-001
1 repeat
Spark occurs in flammable concentration area (Outs LgLk)
Event1070
Q:1e+000
5 repeats
Spark occurs when flammable concentration present (condenser)
Event913
Q:1e-001
5 repeats
Box around electronics does not prevent flame propagation to rest of refrigerant
Event834
Q:1e-004


Non-feed through ignition event
Gate708
Q:6e-012
To Page 3
Refrigerant in flammable concentration range
Gate709
Q:8e-005
Ignition source present (Outs SmLk)
Gate710
Q:7.4e-006
9 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002
1 repeat
Line rupture occurs (Outs SmLk)
Event1132
Q:4.5e-003
10 repeat
No wind
Event172
Q:6e-002
9 repeats
Blower off (outside condenser)
Event173
Q:3e-001
5 repeats
Leak is not noticed in time/no mitigation (outside)
Event174
Q:9.9e-001
Sufficient non-feed through spark present
Gate711
Q:7.4e-006
Open flame not relevant for outdoor scenarios
Gate712
5 repeats
Spark occurs with sufficient energy (condenser)
Event178
Q:9.9e-001
2 repeats
Spark occurs in flammable concentration area (Outs SmLk)
Event179
Q:1e+000
5 repeats
Spark occurs when flammable concentration present (condenser)
Event913
Q:1e-001
5 repeats
Box around electronics does not prevent flame propagation to rest of refrigerant
Event834
Q:1e-004

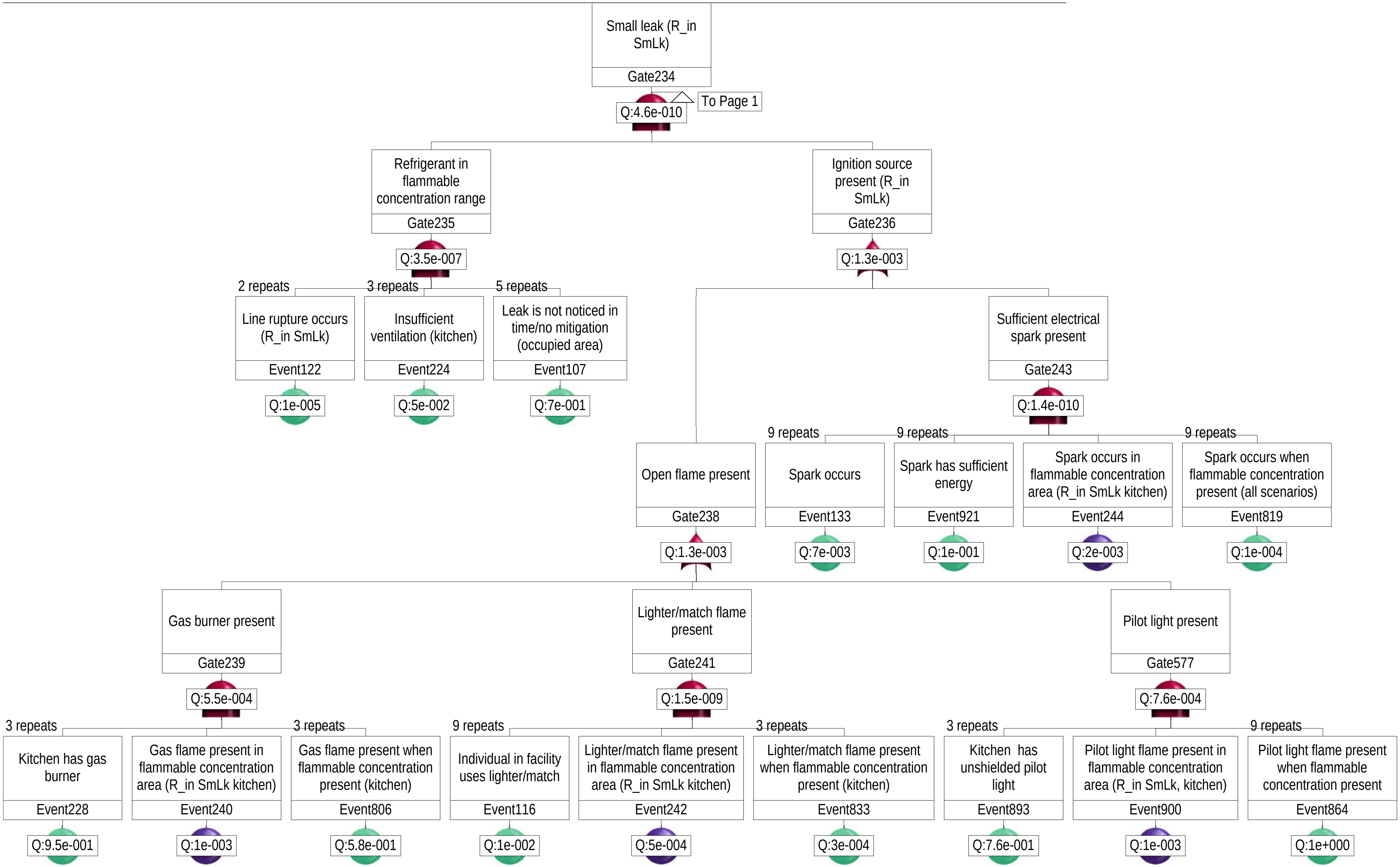

Refrigerant ignition (W_in SmLk)
Gate267
Q:7.8e-010
To Page 2
Refrigerant ignition inside cooler (W_in, SmLk)
Gate645
Q:7e-014
Refrigerant ignition in kitchen (W_in, SmLk)
Gate646
Q:7.8e-010
From Page 7
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Refrigerant in flammable concentration range
Gate647
Q:9.4e-005
Sufficient electrical spark present
Gate651
Q:7.8e-010
3 repeats
Line rupture occurs (W_in, SmLk)
Event155
Q:1e-004
3 repeats
Insufficient ventilation (walk in interior)
Event953
Q:9.9e-001
3 repeats
Leak is not noticed in time/no mitigation (W_in)
Event954
Q:9.5e-001
3 repeats
Spark occurs
Event957
Q:2.6e-003
3 repeats
Spark has sufficient energy
Event958
Q:1e-001
3 repeats
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)
Event959
Q:3e-001
3 repeats
Spark occurs when flammable concentration present (all scenarios)
Event960
Q:1e-004

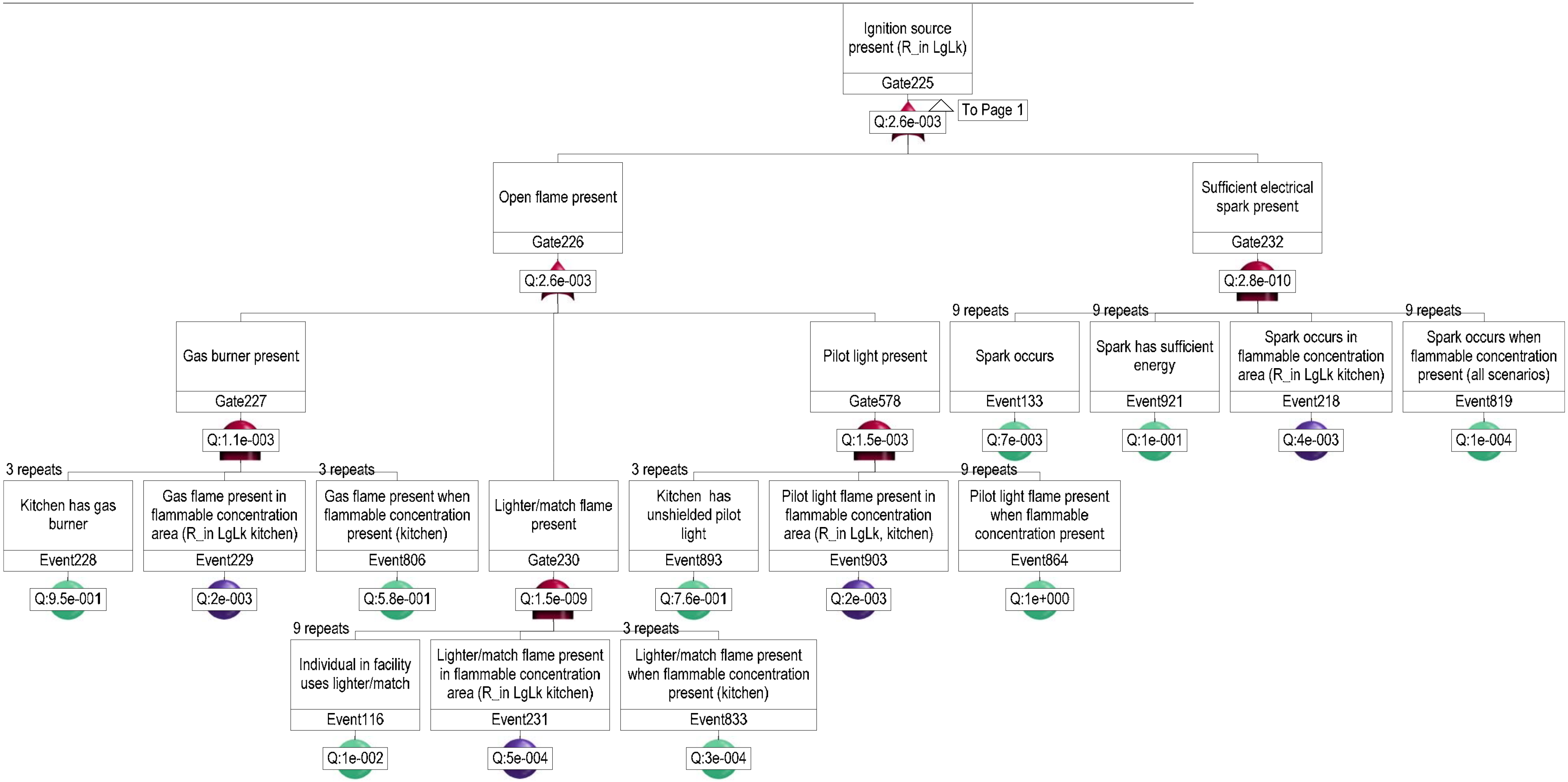

Refrigerant ignition in kitchen (W_in, SmLk)
Gate646
Q:7.8e-010
To Page 6
Cooler door open
Gate660
Q:5e-002
Refrigerant in flammable concentration range
Gate662
Q:4.8e-006
Ignition source present (W_in SmLk)
Gate269
Q:3.3e-003
7 repeats
Cooler door closed
Event973
Q:9.5e-001
3 repeats
Line rupture occurs (W_in, SmLk)
Event155
Q:1e-004
3 repeats
Insufficient ventilation (kitchen)
Event224
Q:5e-002
2 repeats
Leak is not noticed in time/no mitigation (W_in door open)
Event976
Q:9e-001
Sufficient electrical spark present
Gate306
Q:7e-010
Open flame present
Gate301
Q:3.3e-003
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-001
Spark occurs in flammable concentration area (W_in SmLk kitchen)
Event307
Q:1e-002
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate302
Q:1.4e-003
Pilot light present
Gate573
Q:1.9e-003
3 repeats
Kitchen has gas burner
Event228
Q:9.5e-001
Gas flame present in flammable concentration area (W_in SmLk kitchen)
Event303
Q:2.5e-003
3 repeats
Gas flame present when flammable concentration present (kitchen)
Event806
Q:5.8e-001
Lighter/match flame present
Gate304
Q:3.7e-009
3 repeats
Kitchen has unshielded pilot light
Event893
Q:7.6e-001
Pilot light flame present in flammable concentration area (W_in SmLk, kitchen)
Event894
Q:2.5e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (W_in SmLk kitchen)
Event305
Q:1.3e-003
3 repeats
Lighter/match flame present when flammable concentration present (kitchen)
Event833
Q:3e-004

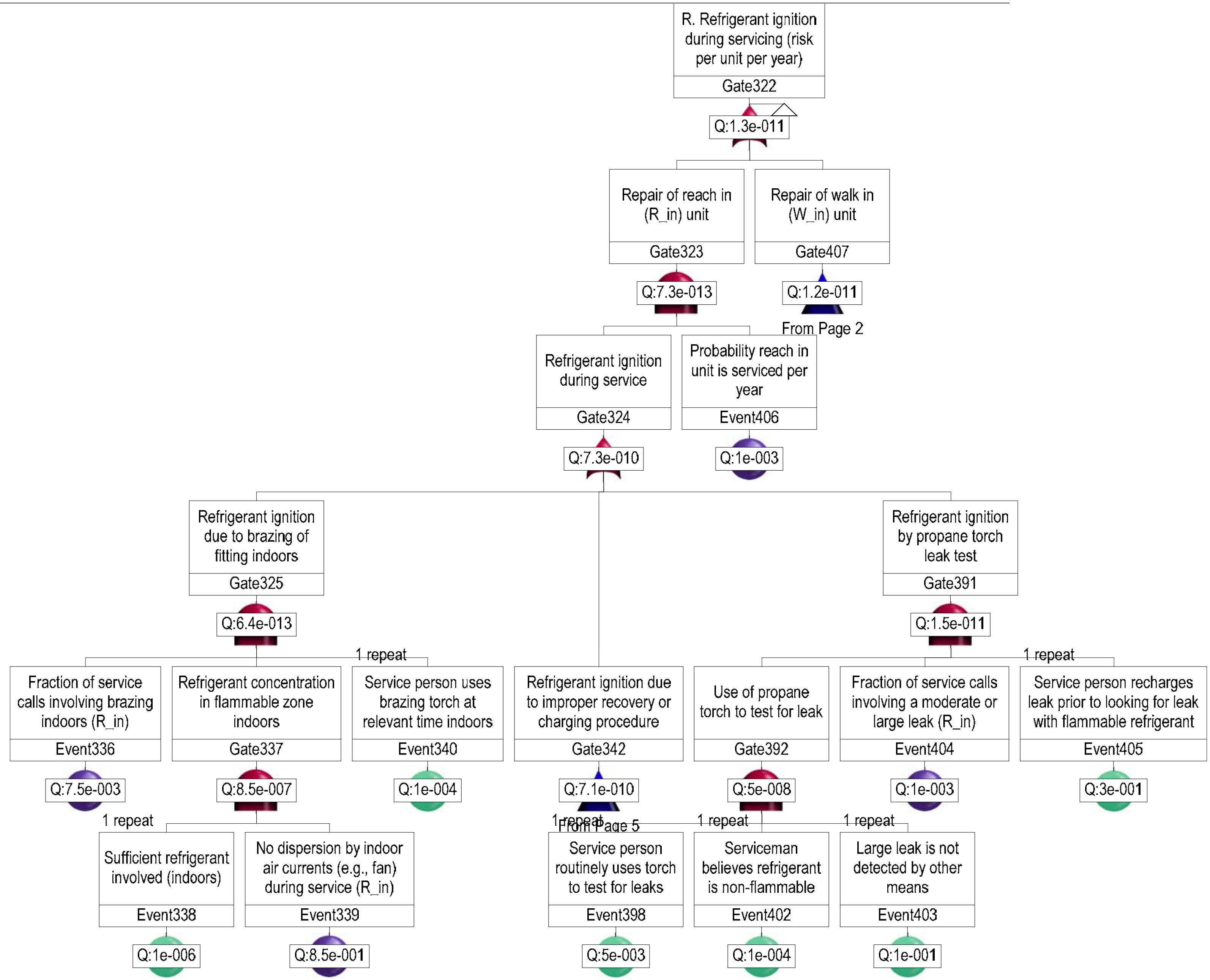
GRADIENT

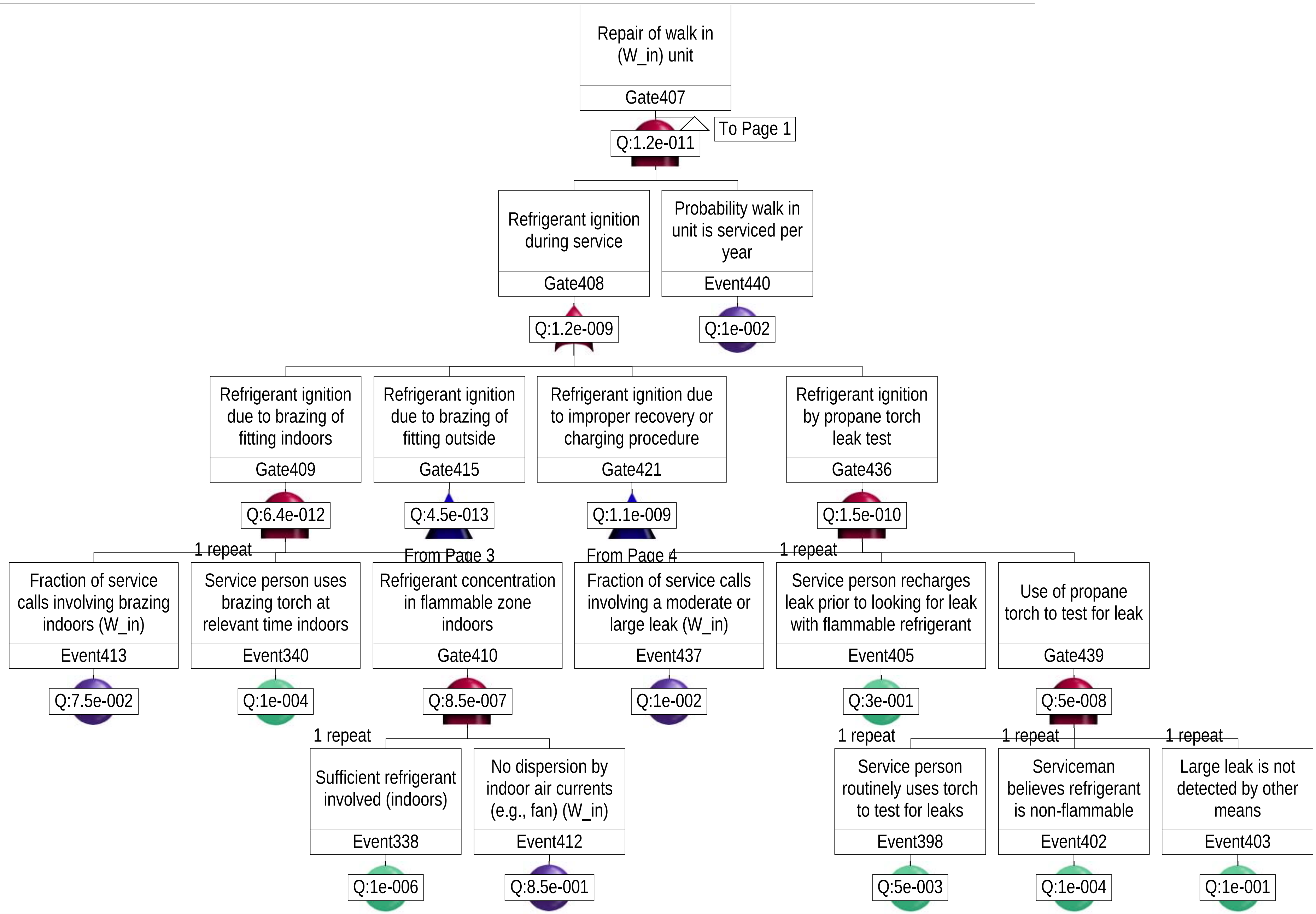


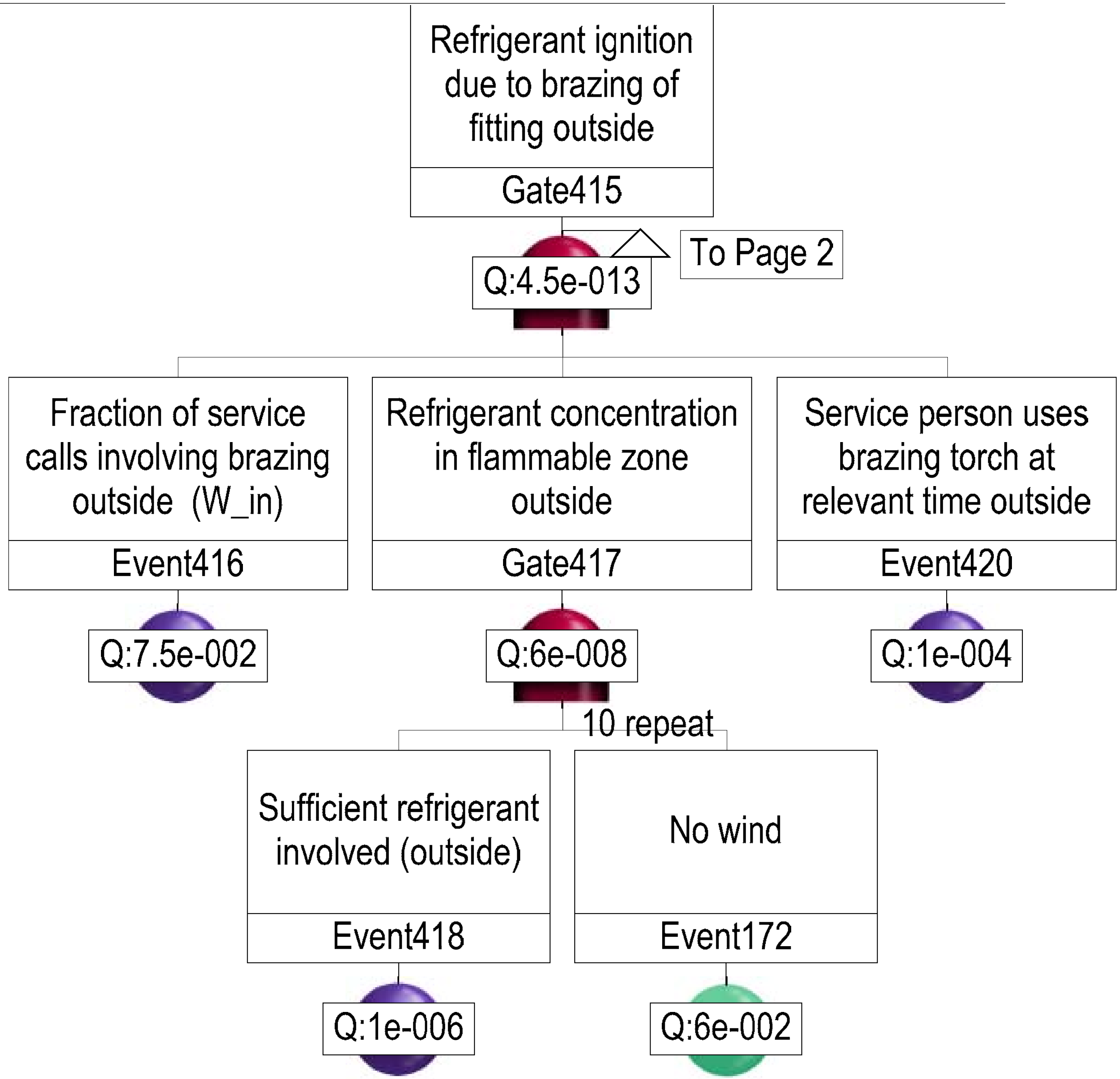
Refrigerant ignition in kitchen (W_in, LgLk)
Gate629
Q:1.6e-010
To Page 2
Cooler door open
Gate633
Q:5e-002
Refrigerant in flammable concentration range
Gate248
Q:4.8e-007
Ignition source present (W_in LgLk)
Gate250
Q:6.5e-003
7 repeats
Cooler door closed
Event973
Q:9.5e-001
3 repeats
Line rupture occurs (W_in, LgLk)
Event140
Q:1e-005
3 repeats
Insufficient ventilation (kitchen)
Event224
Q:5e-002
Leak is not noticed in time/no mitigation (W_in)
Event142
Q:0e+000
Sufficient electrical spark present
Gate265
Q:1.4e-009
Open flame present
Gate251
Q:6.5e-003
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-001
Spark occurs in flammable concentration area (W_in LgLk kitchen)
Event266
Q:2e-002
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate252
Q:2.8e-003
Pilot light present
Gate575
Q:3.8e-003
3 repeats
Kitchen has gas burner
Event228
Q:9.5e-001
Gas flame present in flammable concentration area (W_in LgLk kitchen)
Event253
Q:5e-003
3 repeats
Gas flame present when flammable concentration present (kitchen)
Event806
Q:5.8e-001
Lighter/match flame present
Gate261
Q:7.5e-009
3 repeats
Kitchen has unshielded pilot light
Event893
Q:7.6e-001
Pilot light flame present in flammable concentration area (W_in LgLk, kitchen)
Event897
Q:5e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (W_in LgLk kitchen)
Event262
Q:2.5e-003
3 repeats
Lighter/match flame present when flammable concentration present (kitchen)
Event833
Q:3e-004

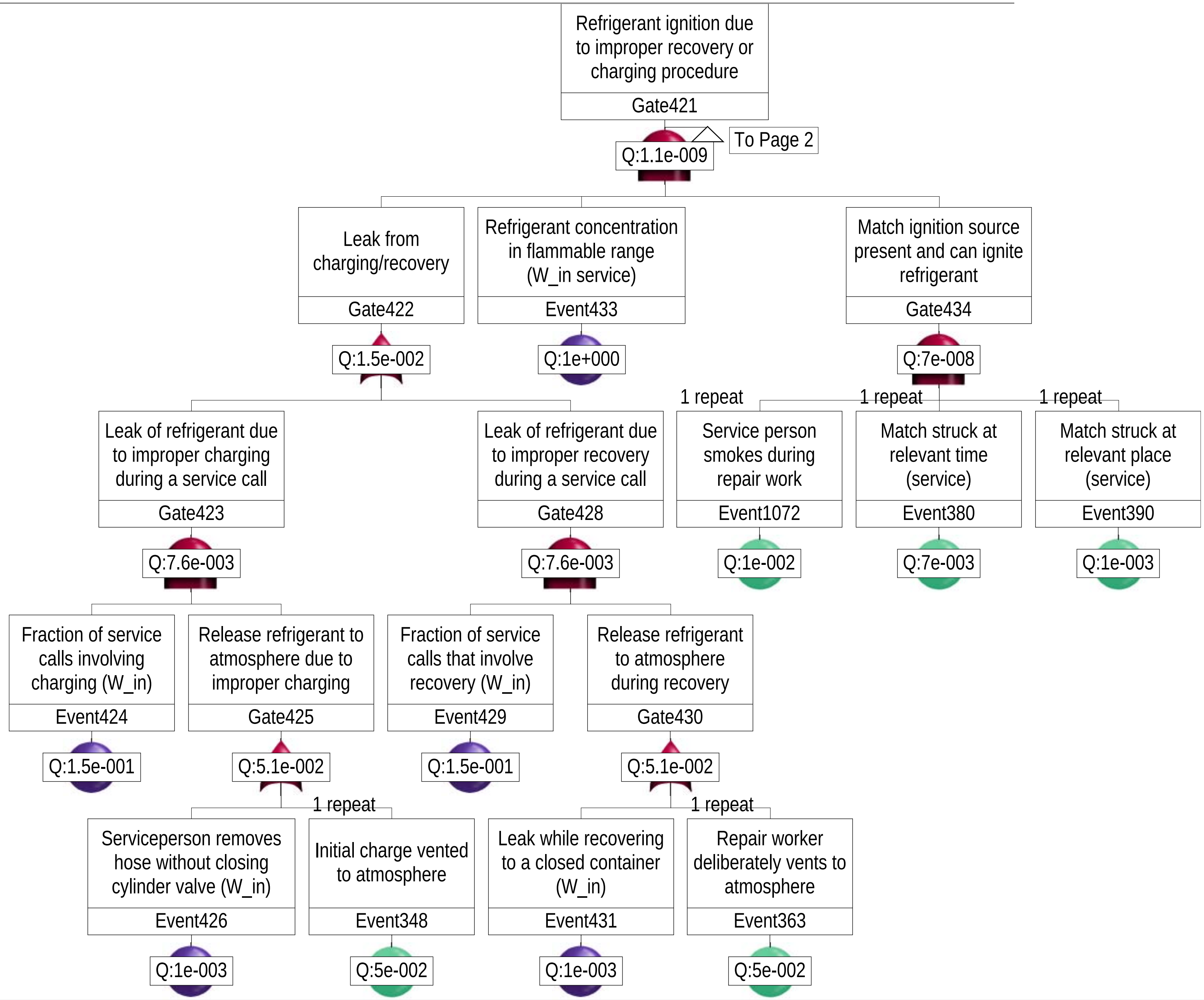

Small leak (R_in SmLk)
Gate234
Q:4.6e-010
To Page 1
Refrigerant in flammable concentration range
Gate235
Q:3.5e-007
Ignition source present (R_in SmLk)
Gate236
Q:1.3e-003
2 repeats
Line rupture occurs (R_in SmLk)
Event122
Q:1e-005
3 repeats
Insufficient ventilation (kitchen)
Event224
Q:5e-002
5 repeats
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001
Sufficient electrical spark present
Gate243
Q:1.4e-010
Open flame present
Gate238
Q:1.3e-003
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-001
Spark occurs in flammable concentration area (R_in SmLk kitchen)
Event244
Q:2e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate239
Q:5.5e-004
Lighter/match flame present
Gate241
Q:1.5e-009
Pilot light present
Gate577
Q:7.6e-004
3 repeats
Kitchen has gas burner
Event228
Q:9.5e-001
Gas flame present in flammable concentration area (R_in SmLk kitchen)
Event240
Q:1e-003
3 repeats
Gas flame present when flammable concentration present (kitchen)
Event806
Q:5.8e-001
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in SmLk kitchen)
Event242
Q:5e-004
3 repeats
Lighter/match flame present when flammable concentration present (kitchen)
Event833
Q:3e-004
3 repeats
Kitchen has unshielded pilot light
Event893
Q:7.6e-001
Pilot light flame present in flammable concentration area (R_in SmLk, kitchen)
Event900
Q:1e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000

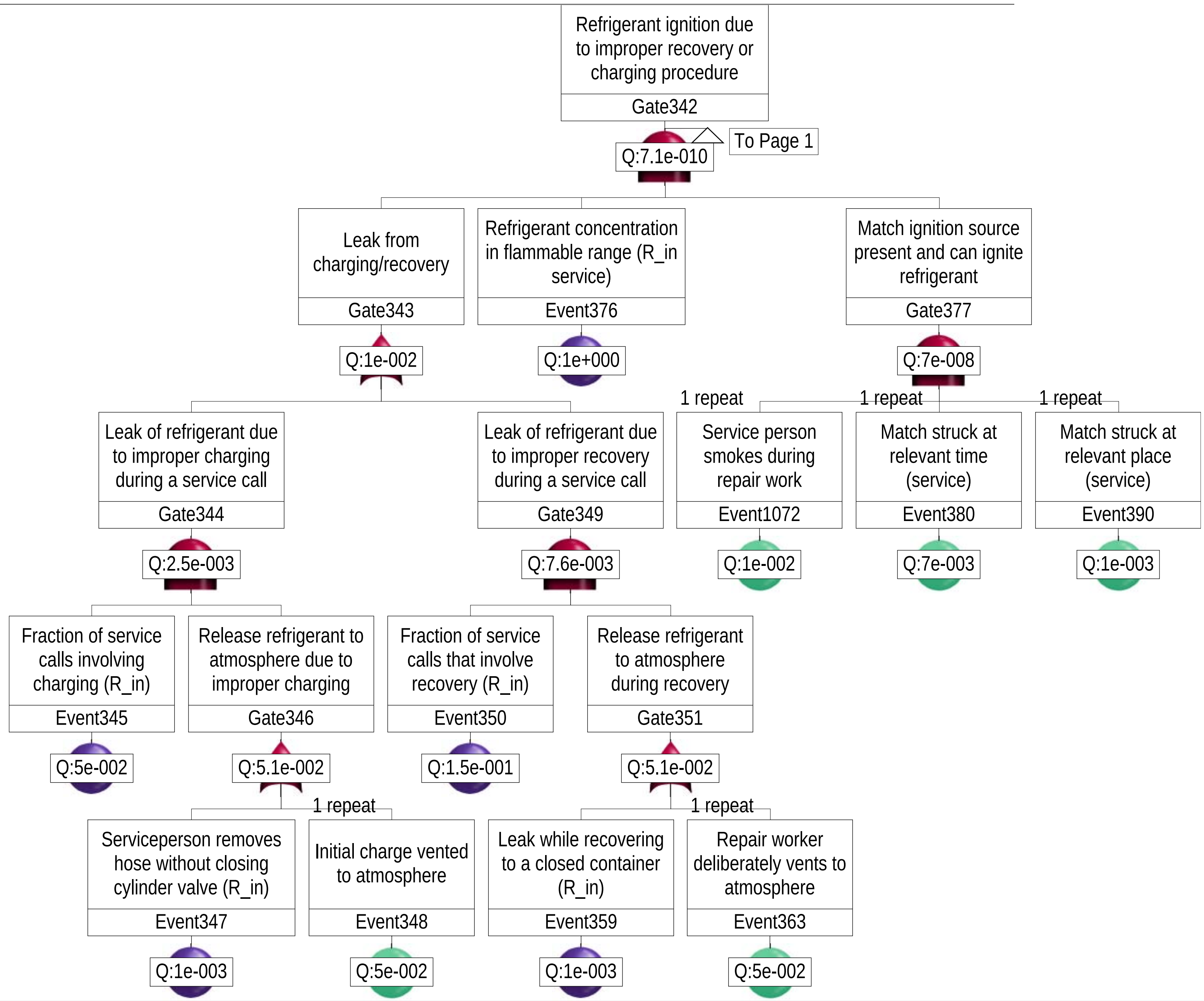

Ignition source present (R_in LgLk)
Gate225
Q:2.6e-003
To Page 1
Open flame present
Gate226
Q:2.6e-003
Sufficient electrical spark present
Gate232
Q:2.8e-010
Gas burner present
Gate227
Q:1.1e-003
Pilot light present
Gate578
Q:1.5e-003
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-001
Spark occurs in flammable concentration area (R_in LgLk kitchen)
Event218
Q:4e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
3 repeats
Kitchen has gas burner
Event228
Q:9.5e-001
Gas flame present in flammable concentration area (R_in LgLk kitchen)
Event229
Q:2e-003
3 repeats
Gas flame present when flammable concentration present (kitchen)
Event806
Q:5.8e-001
Lighter/match flame present
Gate230
Q:1.5e-009
3 repeats
Kitchen has unshielded pilot light
Event893
Q:7.6e-001
Pilot light flame present in flammable concentration area (R_in LgLk, kitchen)
Event903
Q:2e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in LgLk kitchen)
Event231
Q:5e-004
3 repeats
Lighter/match flame present when flammable concentration present (kitchen)
Event833
Q:3e-004


R. Refrigerant ignition during servicing (risk per unit per year)
Gate322
Q:1.3e-011
Repair of reach in (R_in) unit
Gate323
Q:7.3e-013
Repair of walk in (W_in) unit
Gate407
Q:1.2e-011
From Page 2
Refrigerant ignition during service
Gate324
Q:7.3e-010
Probability reach in unit is serviced per year
Event406
Q:1e-003
Refrigerant ignition due to brazing of fitting indoors
Gate325
Q:6.4e-013
Refrigerant ignition by propane torch leak test
Gate391
Q:1.5e-011
1 repeat
Fraction of service calls involving brazing indoors (R_in)
Event336
Q:7.5e-003
Refrigerant concentration in flammable zone indoors
Gate337
Q:8.5e-007
Service person uses brazing torch at relevant time indoors
Event340
Q:1e-004
Refrigerant ignition due to improper recovery or charging procedure
Gate342
Q:7.1e-010
From Page 5
Use of propane torch to test for leak
Gate392
Q:5e-008
Fraction of service calls involving a moderate or large leak (R_in)
Event404
Q:1e-003
1 repeat
Service person recharges leak prior to looking for leak with flammable refrigerant
Event405
Q:3e-001
1 repeat
Sufficient refrigerant involved (indoors)
Event338
Q:1e-006
No dispersion by indoor air currents (e.g., fan) during service (R_in)
Event339
Q:8.5e-001
1 repeat
Service person routinely uses torch to test for leaks
Event398
Q:5e-003
1 repeat
Serviceman believes refrigerant is non-flammable
Event402
Q:1e-004
1 repeat
Large leak is not detected by other means
Event403
Q:1e-001

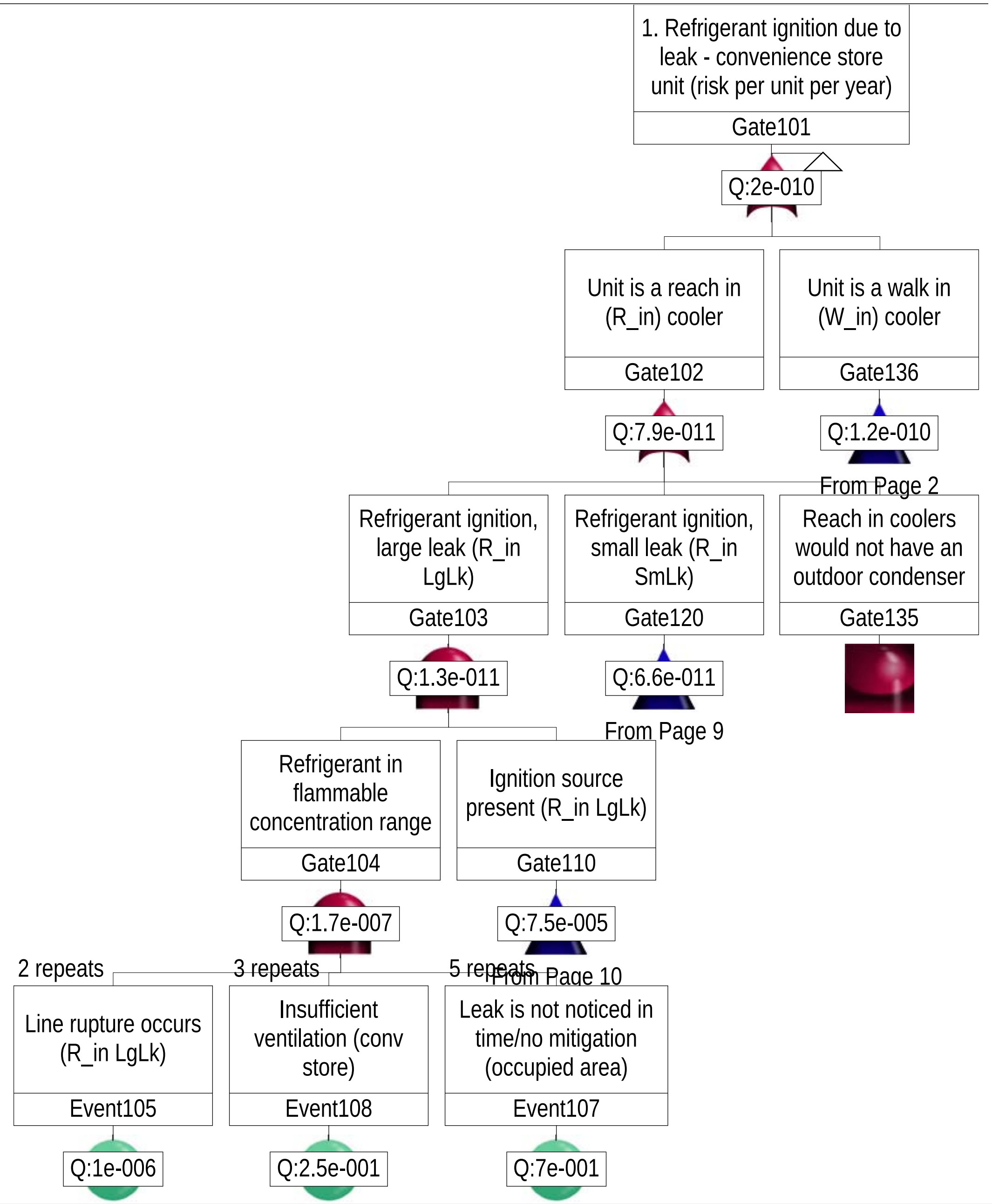

Repair of walk in (W_in) unit
Gate407
Q:1.2e-011
To Page 1
Refrigerant ignition during service
Gate408
Q:1.2e-009
Probability walk in unit is serviced per year
Event440
Q:1e-002
Refrigerant ignition due to brazing of fitting indoors
Gate409
Q:6.4e-012
Refrigerant ignition due to brazing of fitting outside
Gate415
Q:4.5e-013
From Page 3
Refrigerant ignition due to improper recovery or charging procedure
Gate421
Q:1.1e-009
From Page 4
Refrigerant ignition by propane torch leak test
Gate436
Q:1.5e-010
1 repeat
Fraction of service calls involving brazing indoors (W_in)
Event413
Q:7.5e-002
Service person uses brazing torch at relevant time indoors
Event340
Q:1e-004
Refrigerant concentration in flammable zone indoors
Gate410
Q:8.5e-007
Fraction of service calls involving a moderate or large leak (W_in)
Event437
Q:1e-002
1 repeat
Service person recharges leak prior to looking for leak with flammable refrigerant
Event405
Q:3e-001
Use of propane torch to test for leak
Gate439
Q:5e-008
1 repeat
Sufficient refrigerant involved (indoors)
Event338
Q:1e-006
No dispersion by indoor air currents (e.g., fan) (W_in)
Event412
Q:8.5e-001
1 repeat
Service person routinely uses torch to test for leaks
Event398
Q:5e-003
1 repeat
Serviceman believes refrigerant is non-flammable
Event402
Q:1e-004
1 repeat
Large leak is not detected by other means
Event403
Q:1e-001

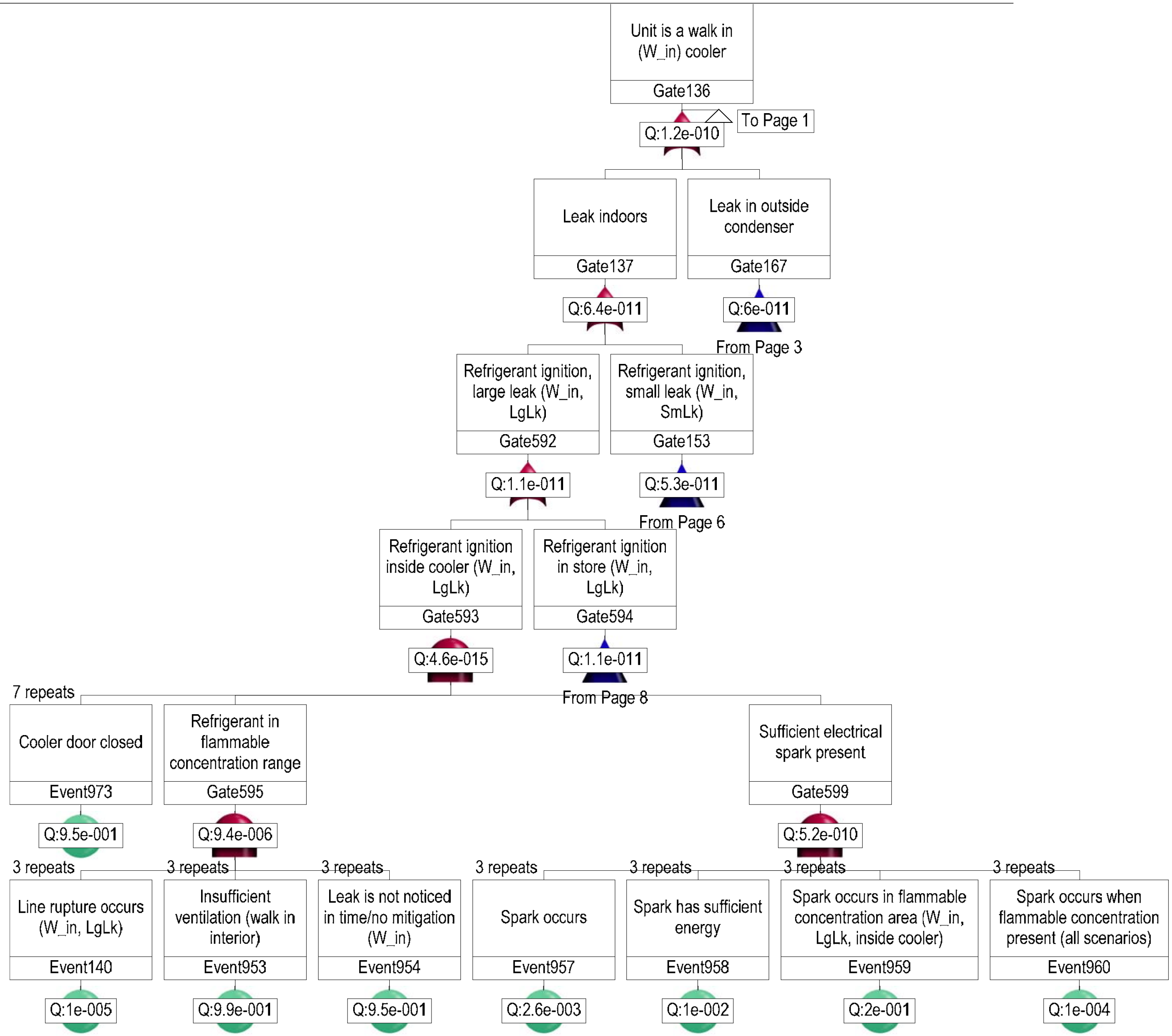

Refrigerant ignition due to brazing of fitting outside
Gate415
Q:4.5e-013
To Page 2
Fraction of service calls involving brazing outside (W_in)
Event416
Q:7.5e-002
Refrigerant concentration in flammable zone outside
Gate417
Q:6e-008
10 repeat
Service person uses brazing torch at relevant time outside
Event420
Q:1e-004
Sufficient refrigerant involved (outside)
Event418
Q:1e-006
No wind
Event172
Q:6e-002

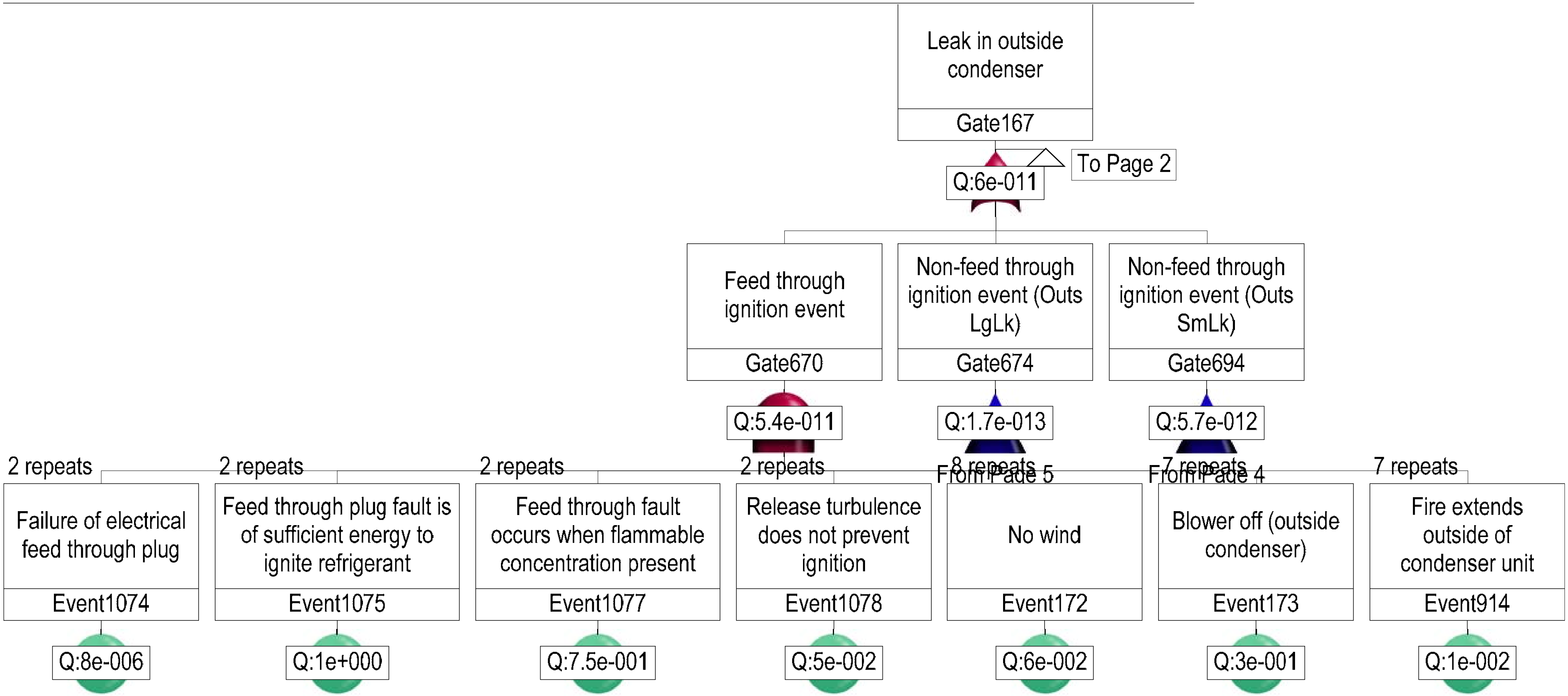

Refrigerant ignition due to improper recovery or charging procedure
Gate421
Q:1.1e-009
To Page 2
Leak from charging/recovery
Gate422
Q:1.5e-002
Refrigerant concentration in flammable range (W_in service)
Event433
Q:1e+000
Match ignition source present and can ignite refrigerant
Gate434
Q:7e-008
Leak of refrigerant due to improper charging during a service call
Gate423
Q:7.6e-003
Leak of refrigerant due to improper recovery during a service call
Gate428
Q:7.6e-003
1 repeat
Service person smokes during repair work
Event1072
Q:1e-002
1 repeat
Match struck at relevant time (service)
Event380
Q:7e-003
1 repeat
Match struck at relevant place (service)
Event390
Q:1e-003
Fraction of service calls involving charging (W_in)
Event424
Q:1.5e-001
Release refrigerant to atmosphere due to improper charging
Gate425
Q:5.1e-002
Fraction of service calls that involve recovery (W_in)
Event429
Q:1.5e-001
Release refrigerant to atmosphere during recovery
Gate430
Q:5.1e-002
Serviceperson removes hose without closing cylinder valve (W_in)
Event426
Q:1e-003
1 repeat
Initial charge vented to atmosphere
Event348
Q:5e-002
Leak while recovering to a closed container (W_in)
Event431
Q:1e-003
1 repeat
Repair worker deliberately vents to atmosphere
Event363
Q:5e-002

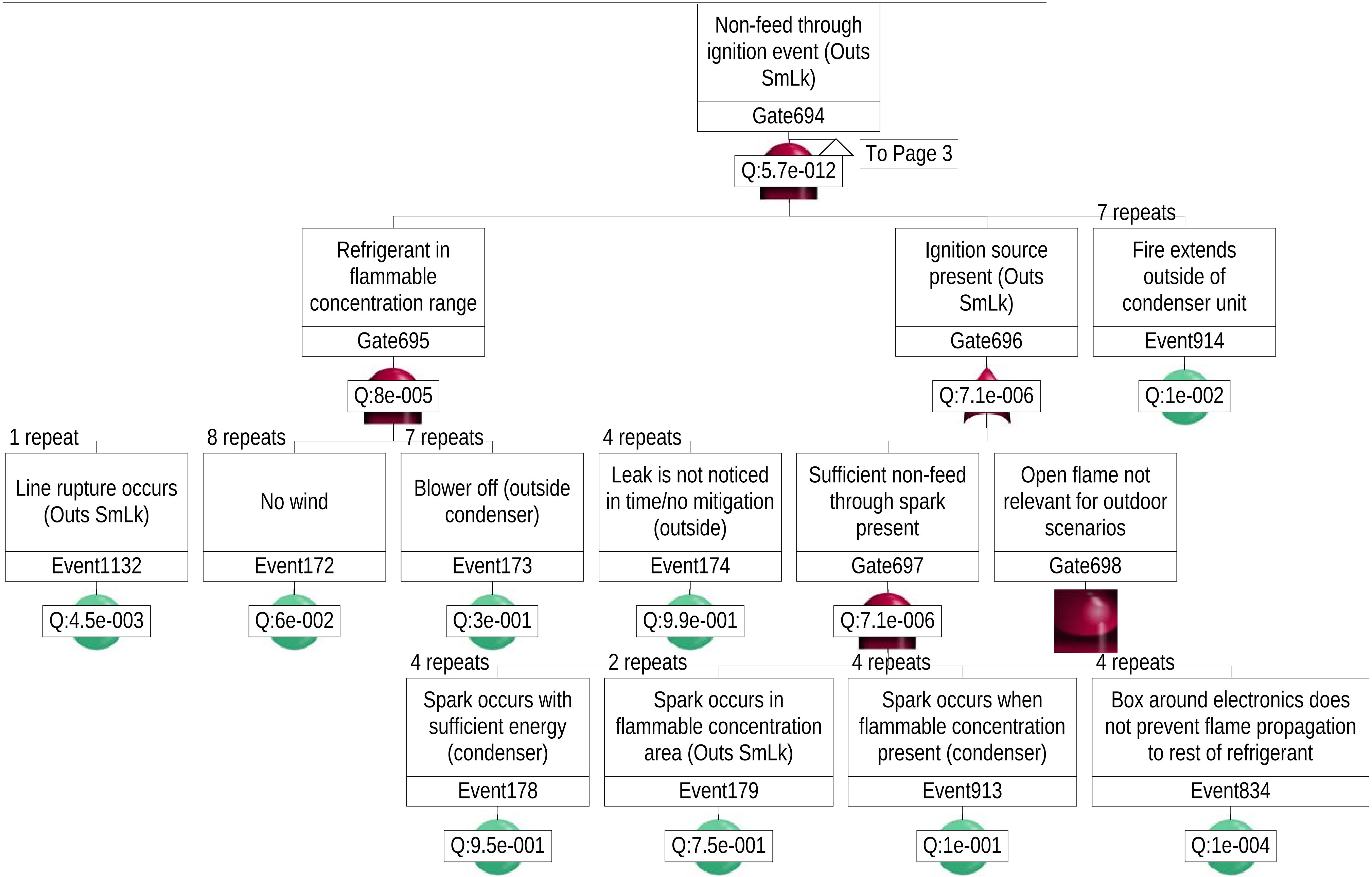

Refrigerant ignition due to improper recovery or charging procedure
Gate342
Q:7.1e-010
To Page 1
Leak from charging/recovery
Gate343
Q:1e-002
Refrigerant concentration in flammable range (R_in service)
Event376
Q:1e+000
Match ignition source present and can ignite refrigerant
Gate377
Q:7e-008
Leak of refrigerant due to improper charging during a service call
Gate344
Q:2.5e-003
Leak of refrigerant due to improper recovery during a service call
Gate349
Q:7.6e-003
1 repeat
Service person smokes during repair work
Event1072
Q:1e-002
1 repeat
Match struck at relevant time (service)
Event380
Q:7e-003
1 repeat
Match struck at relevant place (service)
Event390
Q:1e-003
Fraction of service calls involving charging (R_in)
Event345
Q:5e-002
Release refrigerant to atmosphere due to improper charging
Gate346
Q:5.1e-002
Fraction of service calls that involve recovery (R_in)
Event350
Q:1.5e-001
Release refrigerant to atmosphere during recovery
Gate351
Q:5.1e-002
Serviceperson removes hose without closing cylinder valve (R_in)
Event347
Q:1e-003
1 repeat
Initial charge vented to atmosphere
Event348
Q:5e-002
Leak while recovering to a closed container (R_in)
Event359
Q:1e-003
1 repeat
Repair worker deliberately vents to atmosphere
Event363
Q:5e-002

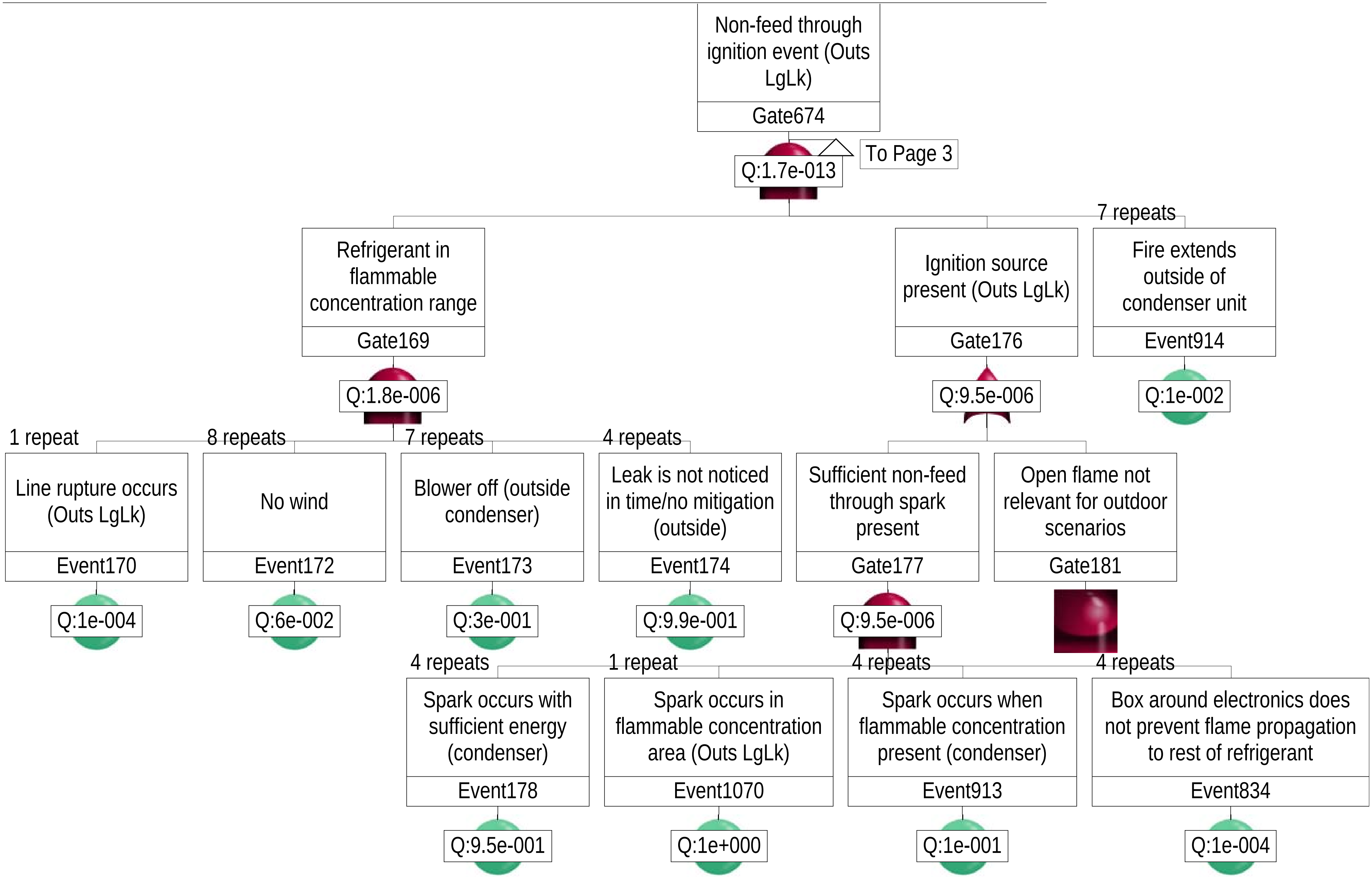
FAULT TREES FOR R-1234yf


1. Refrigerant ignition due to leak - convenience store unit (risk per unit per year)
Gate101
Q:2e-010
Unit is a reach in (R_in) cooler
Gate102
Q:7.9e-011
Unit is a walk in (W_in) cooler
Gate136
Q:1.2e-010
From Page 2
Refrigerant ignition, large leak (R_in LgLk)
Gate103
Q:1.3e-011
Refrigerant ignition, small leak (R_in SmLk)
Gate120
Q:6.6e-011
From Page 9
Reach in coolers would not have an outdoor condenser
Gate135
Refrigerant in flammable concentration range
Gate104
Q:1.7e-007
Ignition source present (R_in LgLk)
Gate110
Q:7.5e-005
From Page 10
2 repeats
Line rupture occurs (R_in LgLk)
Event105
Q:1e-006
3 repeats
Insufficient ventilation (conv store)
Event108
Q:2.5e-001
5 repeats
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001

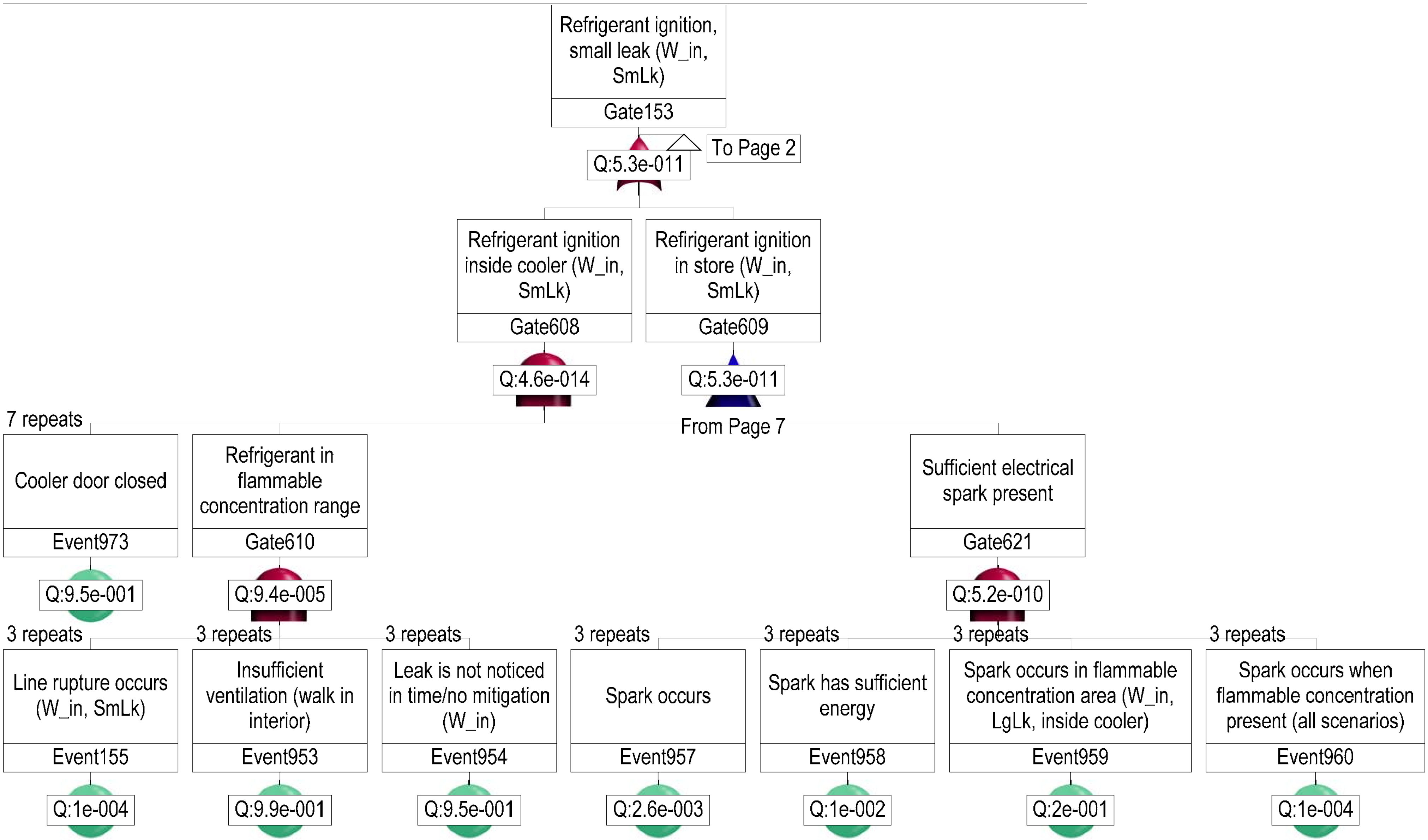

Unit is a walk in (W_in) cooler
Gate136
Q:1.2e-010
To Page 1
Leak indoors
Gate137
Q:6.4e-011
Leak in outside condenser
Gate167
Q:6e-011
From Page 3
Refrigerant ignition, large leak (W_in, LgLk)
Gate592
Q:1.1e-011
Refrigerant ignition, small leak (W_in, SmLk)
Gate153
Q:5.3e-011
From Page 6
Refrigerant ignition inside cooler (W_in, LgLk)
Gate593
Q:4.6e-015
Refrigerant ignition in store (W_in, LgLk)
Gate594
Q:1.1e-011
From Page 8
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Refrigerant in flammable concentration range
Gate595
Q:9.4e-006
Sufficient electrical spark present
Gate599
Q:5.2e-010
3 repeats
Line rupture occurs (W_in, LgLk)
Event140
Q:1e-005
3 repeats
Insufficient ventilation (walk in interior)
Event953
Q:9.9e-001
3 repeats
Leak is not noticed in time/no mitigation (W_in)
Event954
Q:9.5e-001
3 repeats
Spark occurs
Event957
Q:2.6e-003
3 repeats
Spark has sufficient energy
Event958
Q:1e-002
3 repeats
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)
Event959
Q:2e-001
3 repeats
Spark occurs when flammable concentration present (all scenarios)
Event960
Q:1e-004

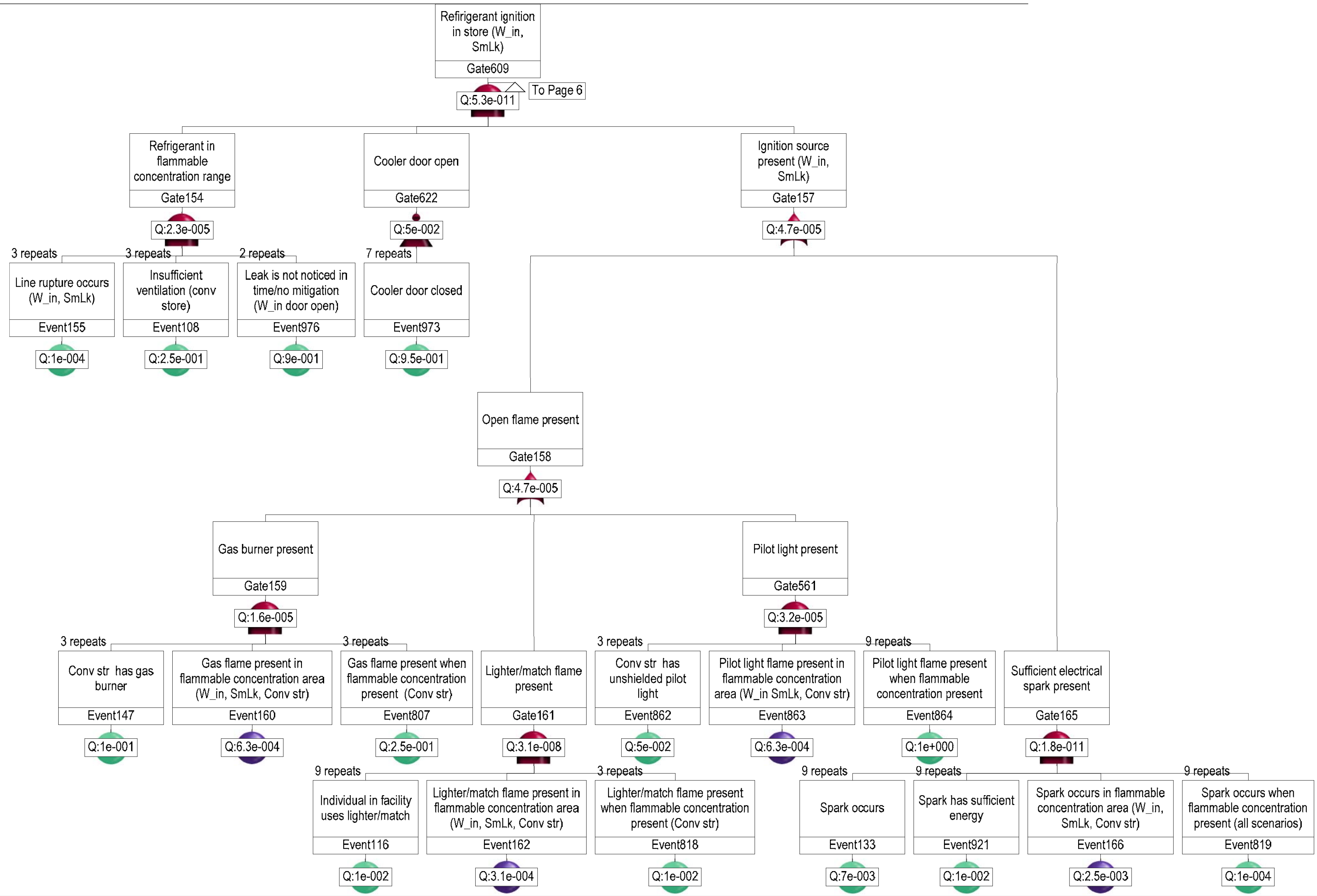

Leak in outside condenser
Gate167
To Page 2
Q:6e-011
Feed through ignition event
Gate670
Q:5.4e-011
Non-feed through ignition event (Outs LgLk)
Gate674
Q:1.7e-013
From Page 5
Non-feed through ignition event (Outs SmLk)
Gate694
Q:5.7e-012
From Page 4
2 repeats
Failure of electrical feed through plug
Event1074
Q:8e-006
2 repeats
Feed through plug fault is of sufficient energy to ignite refrigerant
Event1075
Q:1e+000
2 repeats
Feed through fault occurs when flammable concentration present
Event1077
Q:7.5e-001
2 repeats
Release turbulence does not prevent ignition
Event1078
Q:5e-002
8 repeats
No wind
Event172
Q:6e-002
7 repeats
Blower off (outside condenser)
Event173
Q:3e-001
7 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002


Non-feed through ignition event (Outs SmLk)
Gate694
Q:5.7e-012
To Page 3
Refrigerant in flammable concentration range
Gate695
Q:8e-005
Ignition source present (Outs SmLk)
Gate696
Q:7.1e-006
7 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002
1 repeat
Line rupture occurs (Outs SmLk)
Event1132
Q:4.5e-003
8 repeats
No wind
Event172
Q:6e-002
7 repeats
Blower off (outside condenser)
Event173
Q:3e-001
4 repeats
Leak is not noticed in time/no mitigation (outside)
Event174
Q:9.9e-001
Sufficient non-feed through spark present
Gate697
Q:7.1e-006
Open flame not relevant for outdoor scenarios
Gate698
4 repeats
Spark occurs with sufficient energy (condenser)
Event178
Q:9.5e-001
2 repeats
Spark occurs in flammable concentration area (Outs SmLk)
Event179
Q:7.5e-001
4 repeats
Spark occurs when flammable concentration present (condenser)
Event913
Q:1e-001
4 repeats
Box around electronics does not prevent flame propagation to rest of refrigerant
Event834
Q:1e-004

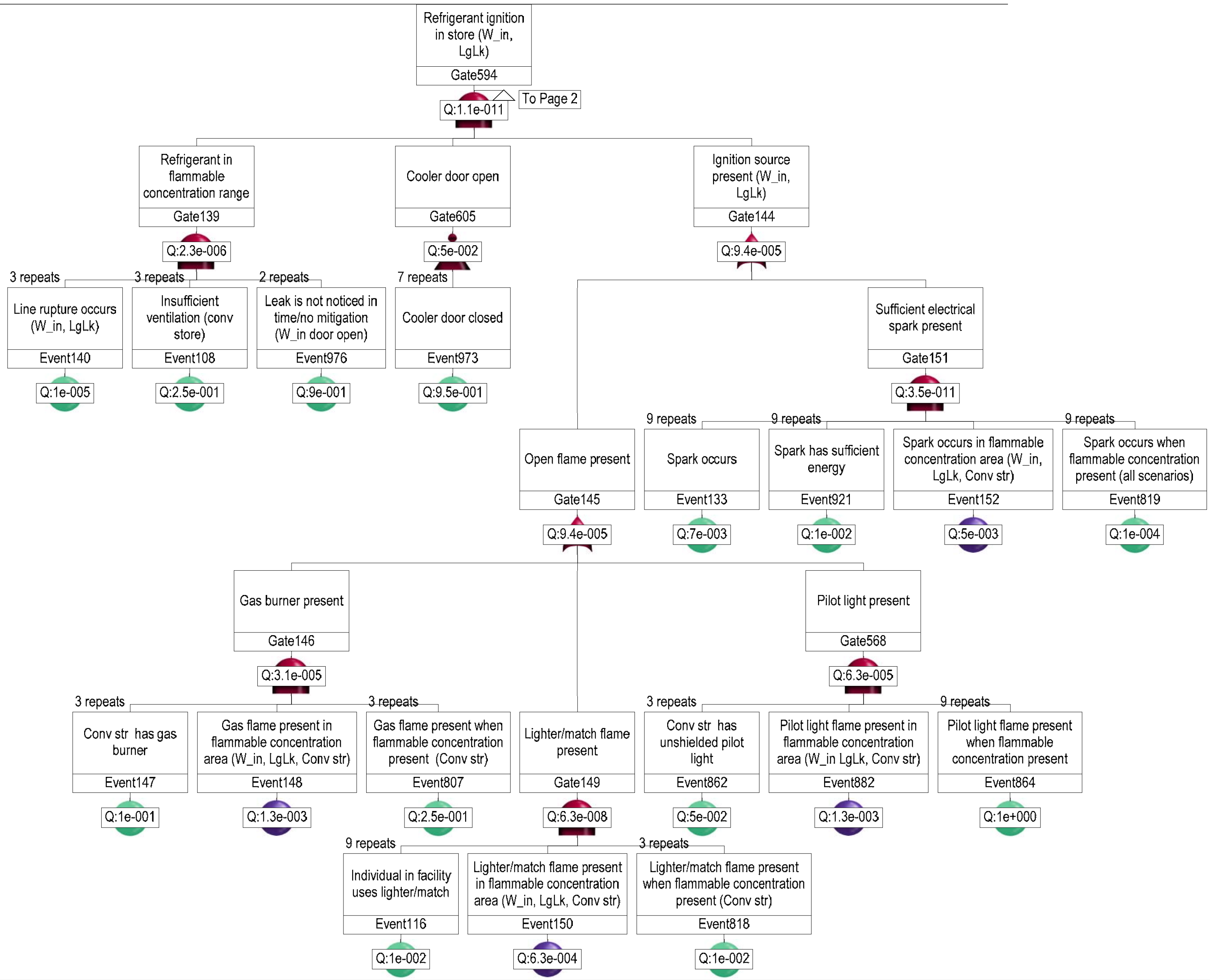

Non-feed through ignition event (Outs LgLk)
Gate674
Q:1.7e-013
To Page 3
Refrigerant in flammable concentration range
Gate169
Q:1.8e-006
Ignition source present (Outs LgLk)
Gate176
Q:9.5e-006
7 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002
1 repeat
Line rupture occurs (Outs LgLk)
Event170
Q:1e-004
8 repeats
No wind
Event172
Q:6e-002
7 repeats
Blower off (outside condenser)
Event173
Q:3e-001
4 repeats
Leak is not noticed in time/no mitigation (outside)
Event174
Q:9.9e-001
Sufficient non-feed through spark present
Gate177
Q:9.5e-006
Open flame not relevant for outdoor scenarios
Gate181
4 repeats
Spark occurs with sufficient energy (condenser)
Event178
Q:9.5e-001
1 repeat
Spark occurs in flammable concentration area (Outs LgLk)
Event1070
Q:1e+000
4 repeats
Spark occurs when flammable concentration present (condenser)
Event913
Q:1e-001
4 repeats
Box around electronics does not prevent flame propagation to rest of refrigerant
Event834
Q:1e-004

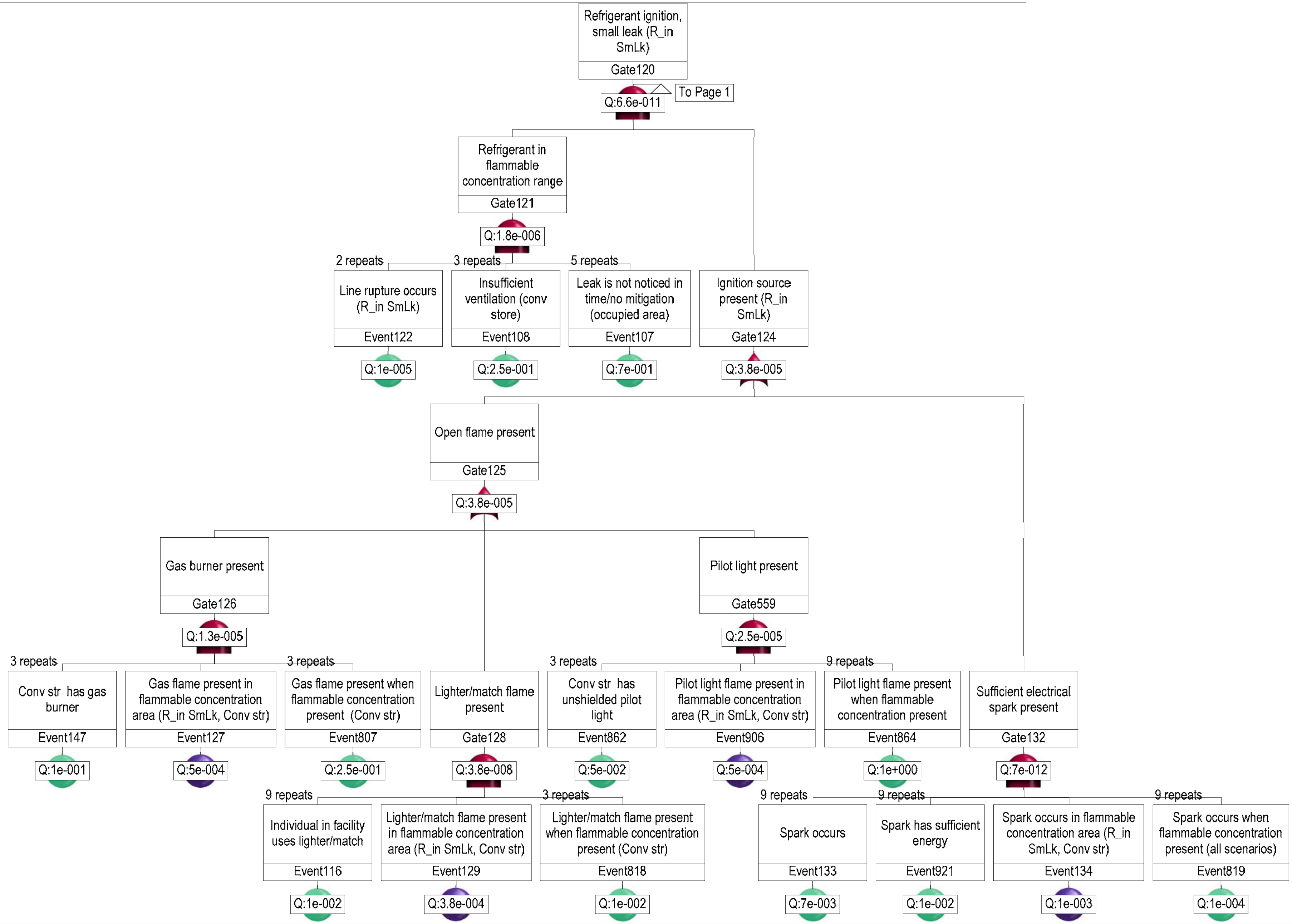
GRADIENT

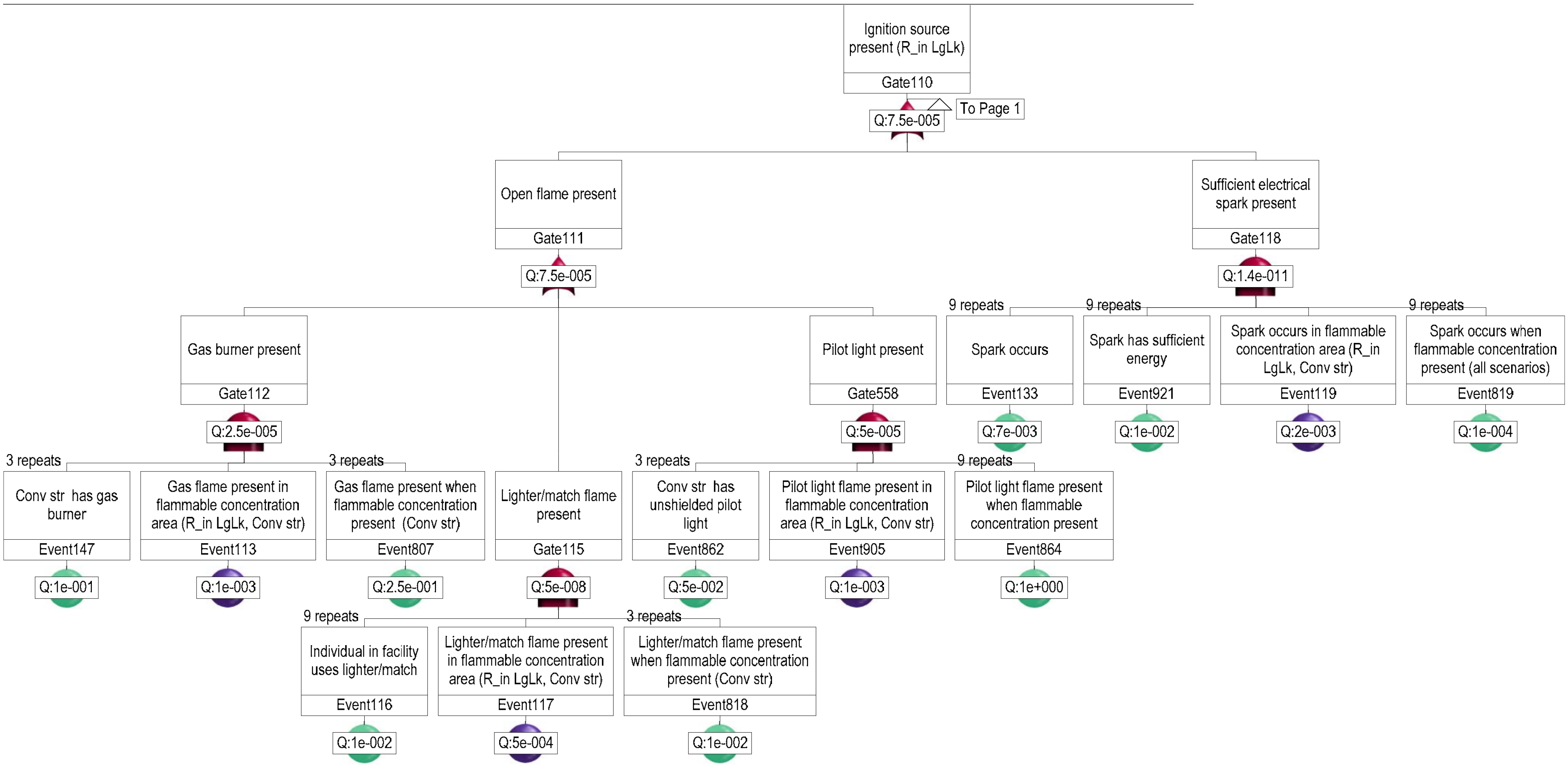

Refrigerant ignition, small leak (W_in, SmLk)
Gate153
Q:5.3e-011
To Page 2
Refrigerant ignition inside cooler (W_in, SmLk)
Gate608
Q:4.6e-014
Refrigerant ignition in store (W_in, SmLk)
Gate609
Q:5.3e-011
From Page 7
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Refrigerant in flammable concentration range
Gate610
Q:9.4e-005
Sufficient electrical spark present
Gate621
Q:5.2e-010
3 repeats
Line rupture occurs (W_in, SmLk)
Event155
Q:1e-004
3 repeats
Insufficient ventilation (walk in interior)
Event953
Q:9.9e-001
3 repeats
Leak is not noticed in time/no mitigation (W_in)
Event954
Q:9.5e-001
3 repeats
Spark occurs
Event957
Q:2.6e-003
3 repeats
Spark has sufficient energy
Event958
Q:1e-002
3 repeats
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)
Event959
Q:2e-001
3 repeats
Spark occurs when flammable concentration present (all scenarios)
Event960
Q:1e-004

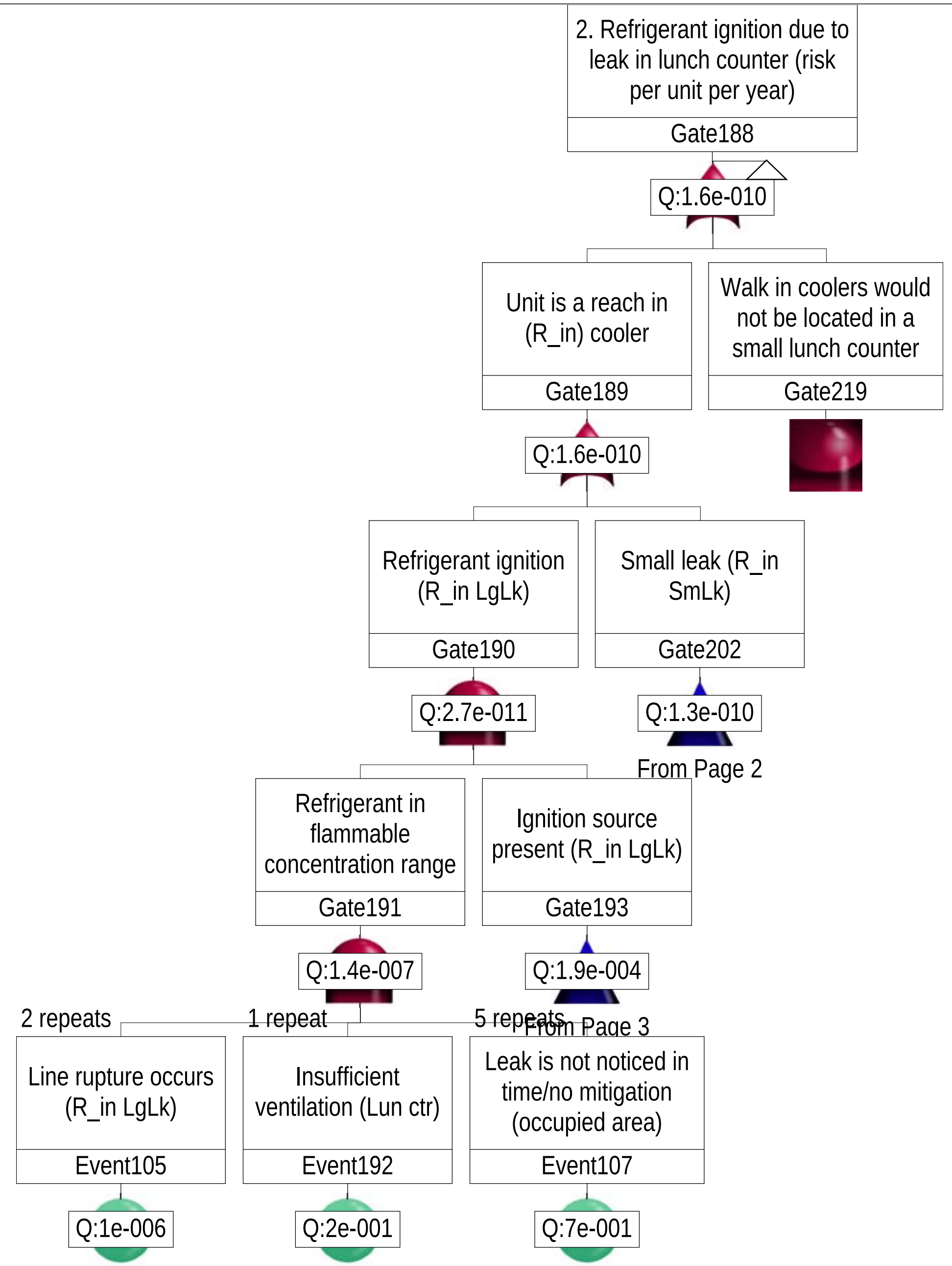


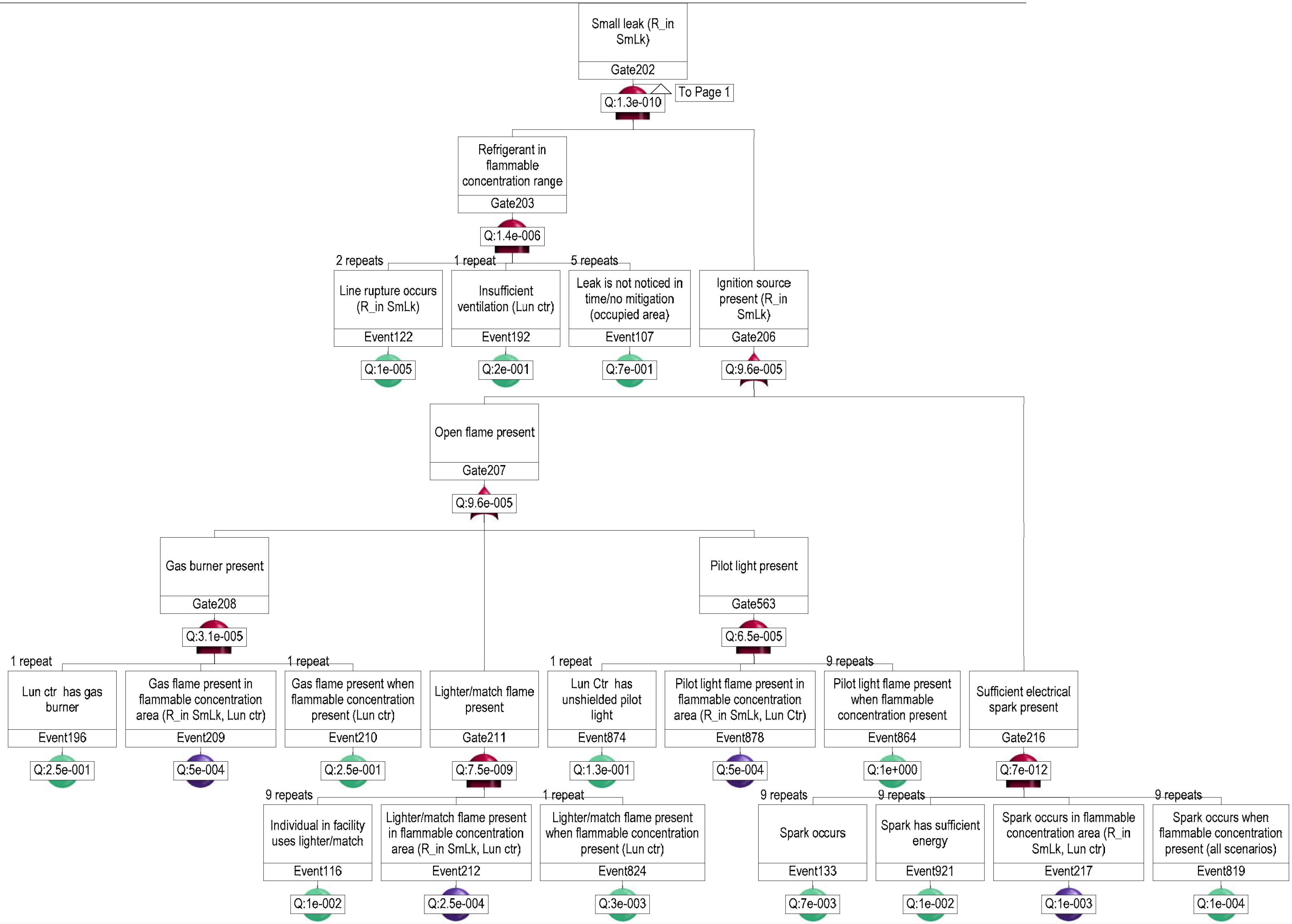
Refrigerant ignition in store (W_in, SmLk)
Gate609
Q:5.3e-011
To Page 6
Refrigerant in flammable concentration range
Gate154
Q:2.3e-005
Cooler door open
Gate622
Q:5e-002
Ignition source present (W_in, SmLk)
Gate157
Q:4.7e-005
3 repeats
Line rupture occurs (W_in, SmLk)
Event155
Q:1e-004
3 repeats
Insufficient ventilation (conv store)
Event108
Q:2.5e-001
2 repeats
Leak is not noticed in time/no mitigation (W_in door open)
Event976
Q:9e-001
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Open flame present
Gate158
Q:4.7e-005
Gas burner present
Gate159
Q:1.6e-005
Pilot light present
Gate561
Q:3.2e-005
3 repeats
Conv str has gas burner
Event147
Q:1e-001
Gas flame present in flammable concentration area (W_in, SmLk, Conv str)
Event160
Q:6.3e-004
3 repeats
Gas flame present when flammable concentration present (Conv str)
Event807
Q:2.5e-001
Lighter/match flame present
Gate161
Q:3.1e-008
3 repeats
Conv str has unshielded pilot light
Event862
Q:5e-002
Pilot light flame present in flammable concentration area (W_in SmLk, Conv str)
Event863
Q:6.3e-004
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
Sufficient electrical spark present
Gate165
Q:1.8e-011
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (W_in, SmLk, Conv str)
Event162
Q:3.1e-004
3 repeats
Lighter/match flame present when flammable concentration present (Conv str)
Event818
Q:1e-002
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (W_in, SmLk, Conv str)
Event166
Q:2.5e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004

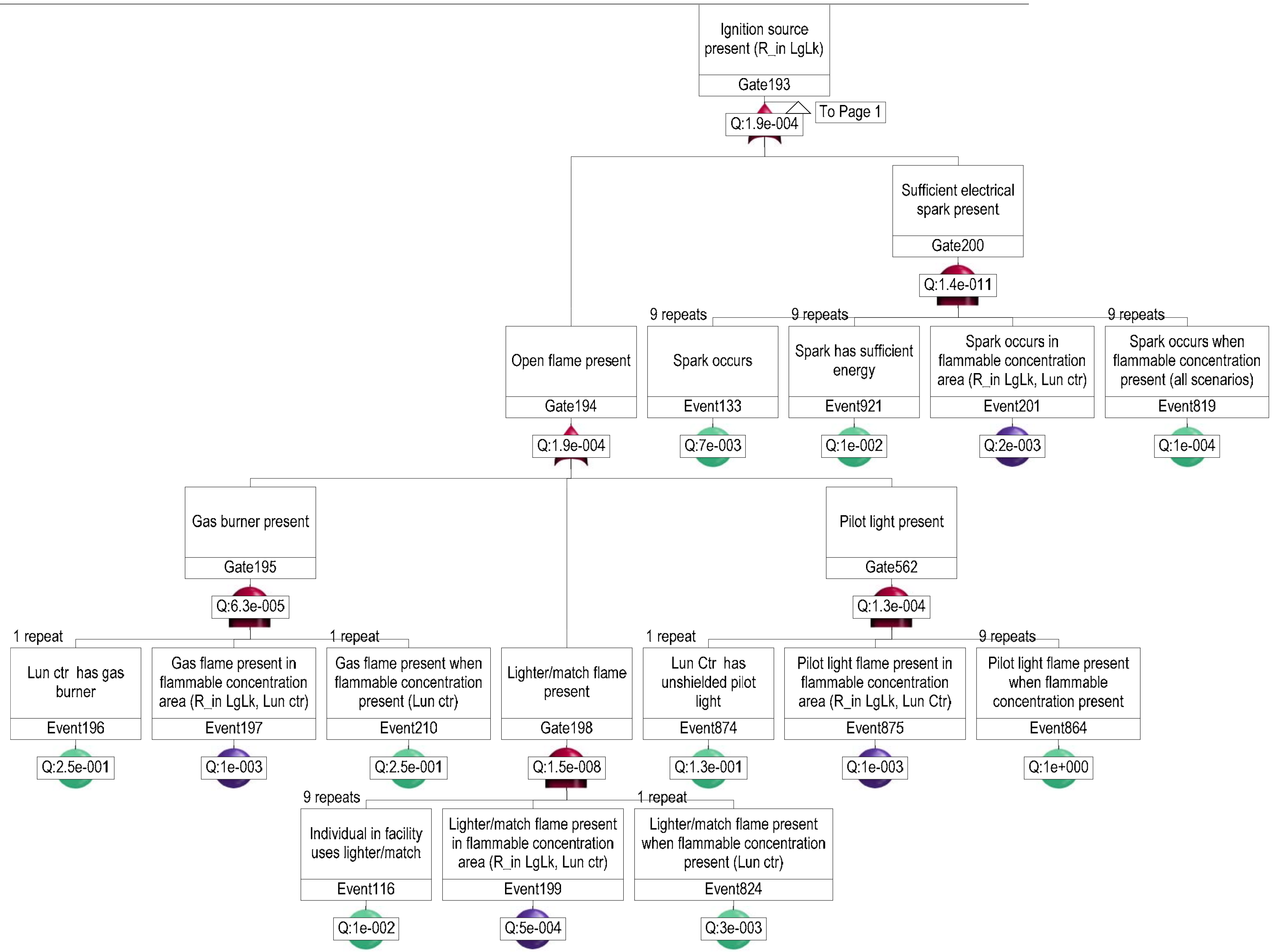

Refrigerant ignition in store (W_in, LgLk)
Gate594
Q:1.1e-011
To Page 2
Refrigerant in flammable concentration range
Gate139
Q:2.3e-006
Cooler door open
Gate605
Q:5e-002
Ignition source present (W_in, LgLk)
Gate144
Q:9.4e-005
3 repeats
Line rupture occurs (W_in, LgLk)
Event140
Q:1e-005
3 repeats
Insufficient ventilation (conv store)
Event108
Q:2.5e-001
2 repeats
Leak is not noticed in time/no mitigation (W_in door open)
Event976
Q:9e-001
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Sufficient electrical spark present
Gate151
Q:3.5e-011
Open flame present
Gate145
Q:9.4e-005
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (W_in, LgLk, Conv str)
Event152
Q:5e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate146
Q:3.1e-005
Pilot light present
Gate568
Q:6.3e-005
3 repeats
Conv str has gas burner
Event147
Q:1e-001
Gas flame present in flammable concentration area (W_in, LgLk, Conv str)
Event148
Q:1.3e-003
3 repeats
Gas flame present when flammable concentration present (Conv str)
Event807
Q:2.5e-001
Lighter/match flame present
Gate149
Q:6.3e-008
3 repeats
Conv str has unshielded pilot light
Event862
Q:5e-002
Pilot light flame present in flammable concentration area (W_in LgLk, Conv str)
Event882
Q:1.3e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (W_in, LgLk, Conv str)
Event150
Q:6.3e-004
3 repeats
Lighter/match flame present when flammable concentration present (Conv str)
Event818
Q:1e-002

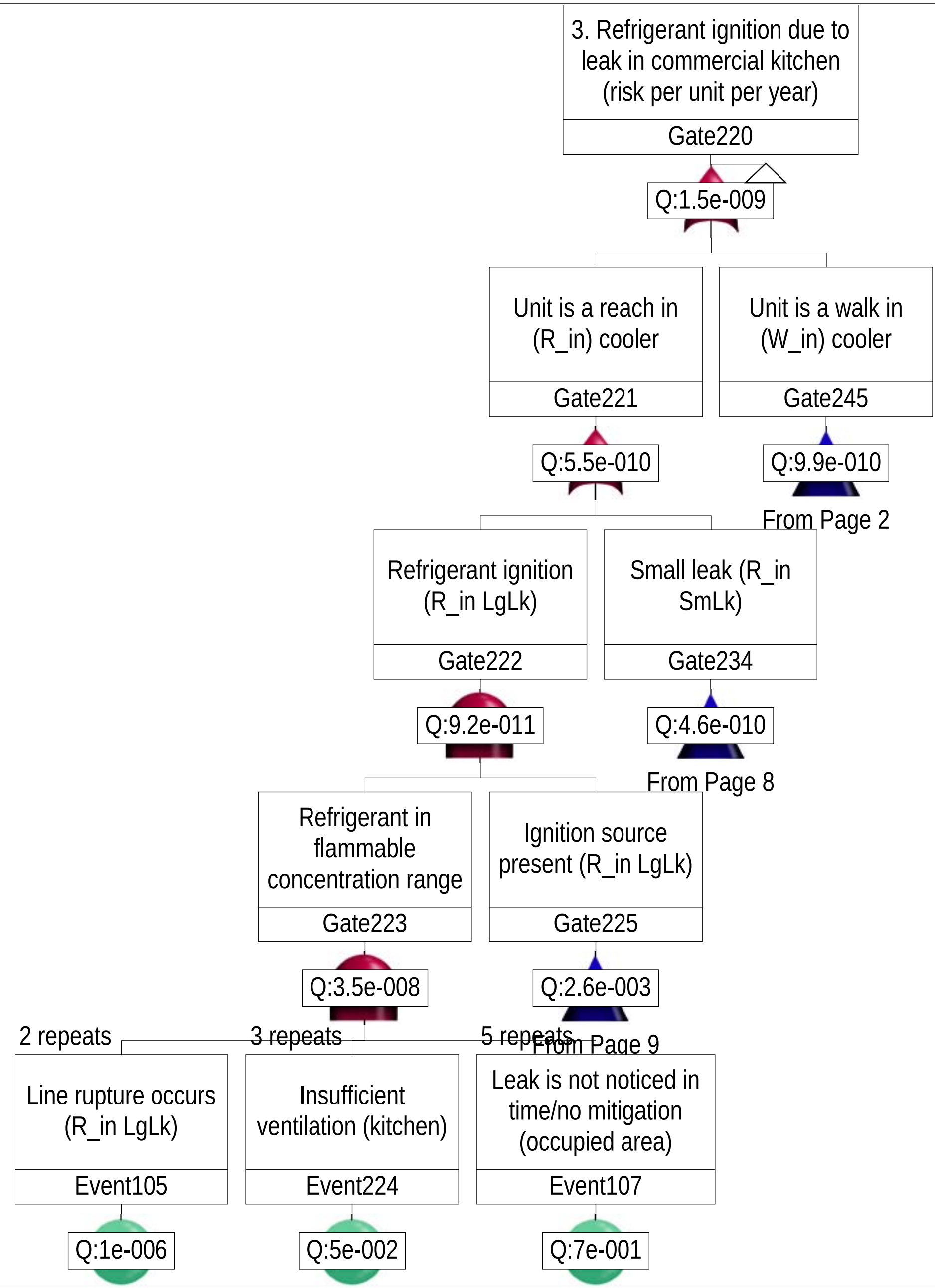

Refrigerant ignition, small leak (R_in SmLk)
Gate120
Q:6.6e-011
To Page 1
Refrigerant in flammable concentration range
Gate121
Q:1.8e-006
2 repeats
Line rupture occurs (R_in SmLk)
Event122
Q:1e-005
3 repeats
Insufficient ventilation (conv store)
Event108
Q:2.5e-001
5 repeats
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001
Ignition source present (R_in SmLk)
Gate124
Q:3.8e-005
Open flame present
Gate125
Q:3.8e-005
Gas burner present
Gate126
Q:1.3e-005
Pilot light present
Gate559
Q:2.5e-005
3 repeats
Conv str has gas burner
Event147
Q:1e-001
Gas flame present in flammable concentration area (R_in SmLk, Conv str)
Event127
Q:5e-004
3 repeats
Gas flame present when flammable concentration present (Conv str)
Event807
Q:2.5e-001
Lighter/match flame present
Gate128
Q:3.8e-008
3 repeats
Conv str has unshielded pilot light
Event862
Q:5e-002
Pilot light flame present in flammable concentration area (R_in SmLk, Conv str)
Event906
Q:5e-004
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
Sufficient electrical spark present
Gate132
Q:7e-012
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in SmLk, Conv str)
Event129
Q:3.8e-004
3 repeats
Lighter/match flame present when flammable concentration present (Conv str)
Event818
Q:1e-002
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (R_in SmLk, Conv str)
Event134
Q:1e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004

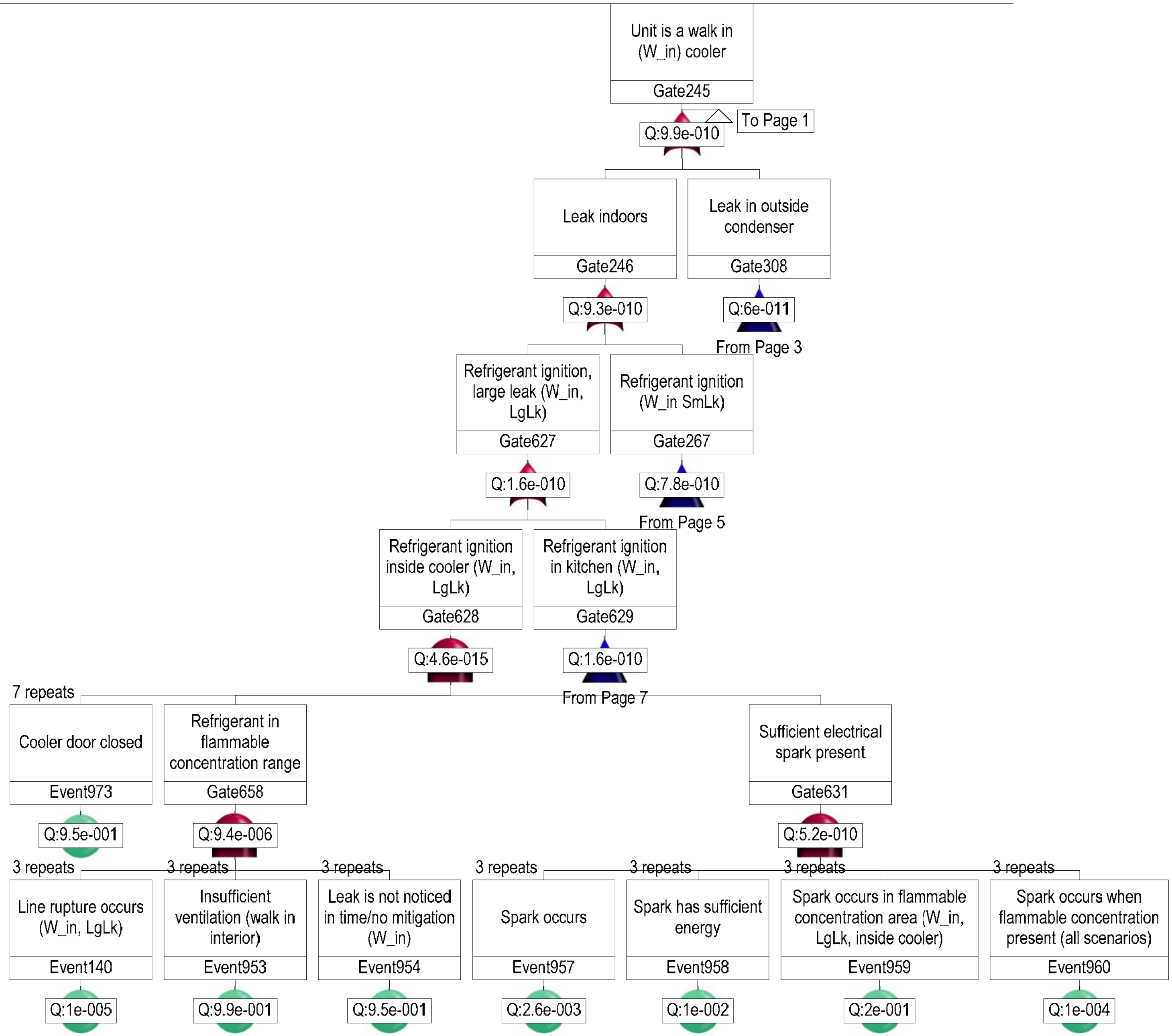

Ignition source present (R_in LgLk)
Gate110
Q:7.5e-005
To Page 1
Open flame present
Gate111
Q:7.5e-005
Sufficient electrical spark present
Gate118
Q:1.4e-011
Gas burner present
Gate112
Q:2.5e-005
Pilot light present
Gate558
Q:5e-005
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (R_in LgLk, Conv str)
Event119
Q:2e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
3 repeats
Conv str has gas burner
Event147
Q:1e-001
Gas flame present in flammable concentration area (R_in LgLk, Conv str)
Event113
Q:1e-003
3 repeats
Gas flame present when flammable concentration present (Conv str)
Event807
Q:2.5e-001
Lighter/match flame present
Gate115
Q:5e-008
3 repeats
Conv str has unshielded pilot light
Event862
Q:5e-002
Pilot light flame present in flammable concentration area (R_in LgLk, Conv str)
Event905
Q:1e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in LgLk, Conv str)
Event117
Q:5e-004
3 repeats
Lighter/match flame present when flammable concentration present (Conv str)
Event818
Q:1e-002


2. Refrigerant ignition due to leak in lunch counter (risk per unit per year)
Gate188
Q:1.6e-010
Unit is a reach in (R_in) cooler
Gate189
Walk in coolers would not be located in a small lunch counter
Gate219
Q:1.6e-010
Refrigerant ignition (R_in LgLk)
Gate190
Small leak (R_in SmLk)
Gate202
Q:2.7e-011
Q:1.3e-010
From Page 2
Refrigerant in flammable concentration range
Gate191
Ignition source present (R_in LgLk)
Gate193
Q:1.4e-007
Q:1.9e-004
2 repeats
1 repeat
5 repeats
From Page 3
Line rupture occurs (R_in LgLk)
Event105
Insufficient ventilation (Lun ctr)
Event192
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:1e-006
Q:2e-001
Q:7e-001

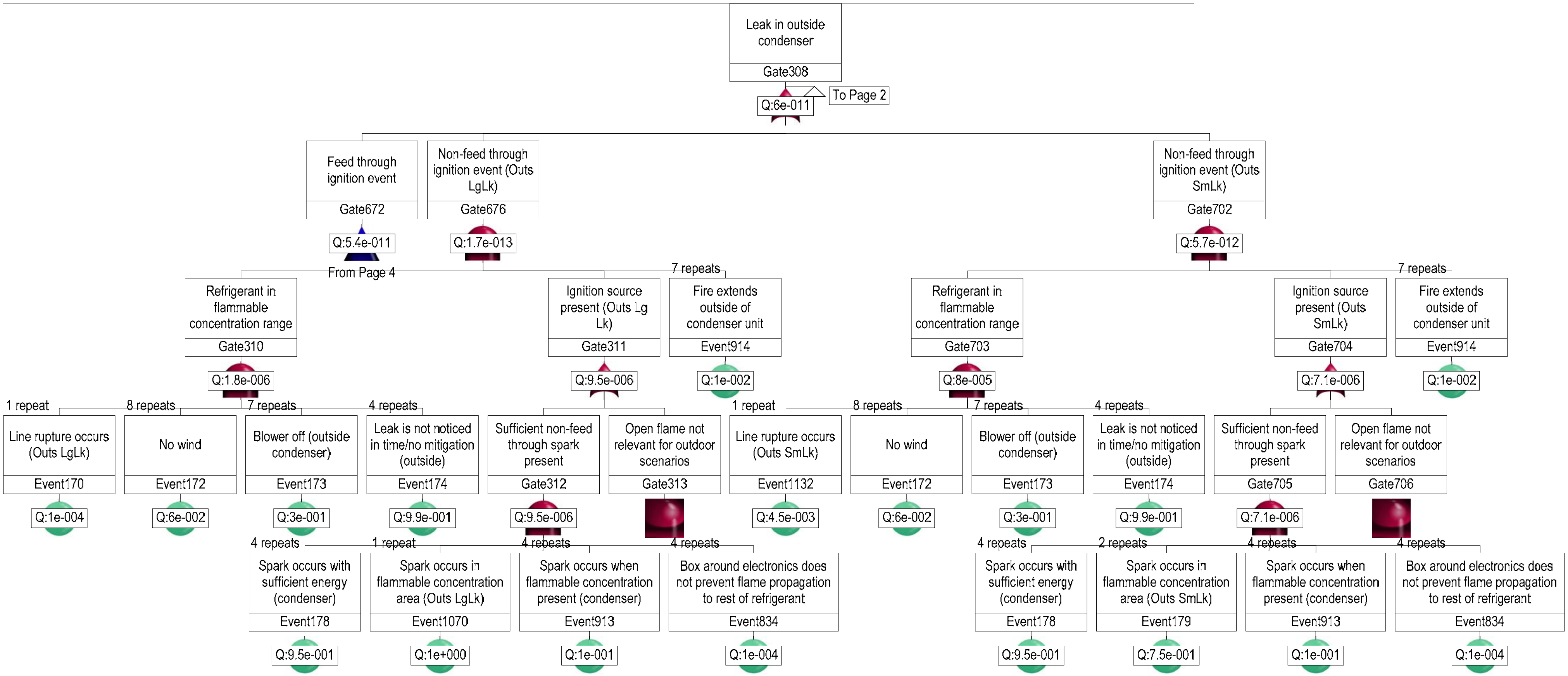

Small leak (R_in SmLk)
Gate202
Q:1.3e-010
To Page 1
Refrigerant in flammable concentration range
Gate203
Q:1.4e-006
2 repeats
Line rupture occurs (R_in SmLk)
Event122
Q:1e-005
1 repeat
Insufficient ventilation (Lun ctr)
Event192
Q:2e-001
5 repeats
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001
Ignition source present (R_in SmLk)
Gate206
Q:9.6e-005
Open flame present
Gate207
Q:9.6e-005
Gas burner present
Gate208
Q:3.1e-005
Pilot light present
Gate563
Q:6.5e-005
1 repeat
Lun ctr has gas burner
Event196
Q:2.5e-001
Gas flame present in flammable concentration area (R_in SmLk, Lun ctr)
Event209
Q:5e-004
1 repeat
Gas flame present when flammable concentration present (Lun ctr)
Event210
Q:2.5e-001
Lighter/match flame present
Gate211
Q:7.5e-009
1 repeat
Lun Ctr has unshielded pilot light
Event874
Q:1.3e-001
Pilot light flame present in flammable concentration area (R_in SmLk, Lun Ctr)
Event878
Q:5e-004
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
Sufficient electrical spark present
Gate216
Q:7e-012
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in SmLk, Lun ctr)
Event212
Q:2.5e-004
1 repeat
Lighter/match flame present when flammable concentration present (Lun ctr)
Event824
Q:3e-003
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (R_in SmLk, Lun ctr)
Event217
Q:1e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004


Ignition source present (R_in LgLk)
Gate193
Q:1.9e-004
To Page 1
Sufficient electrical spark present
Gate200
Q:1.4e-011
9 repeats
9 repeats
9 repeats
Open flame present
Gate194
Q:1.9e-004
Spark occurs
Event133
Q:7e-003
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (R_in LgLk, Lun ctr)
Event201
Q:2e-003
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate195
Q:6.3e-005
Pilot light present
Gate562
Q:1.3e-004
1 repeat
1 repeat
1 repeat
9 repeats
Lun ctr has gas burner
Event196
Q:2.5e-001
Gas flame present in flammable concentration area (R_in LgLk, Lun ctr)
Event197
Q:1e-003
Gas flame present when flammable concentration present (Lun ctr)
Event210
Q:2.5e-001
Lighter/match flame present
Gate198
Q:1.5e-008
Lun Ctr has unshielded pilot light
Event874
Q:1.3e-001
Pilot light flame present in flammable concentration area (R_in LgLk, Lun Ctr)
Event875
Q:1e-003
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
1 repeat
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in LgLk, Lun ctr)
Event199
Q:5e-004
Lighter/match flame present when flammable concentration present (Lun ctr)
Event824
Q:3e-003


3. Refrigerant ignition due to leak in commercial kitchen (risk per unit per year)
Gate220
Q:1.5e-009
Unit is a reach in (R_in) cooler
Gate221
Q:5.5e-010
Unit is a walk in (W_in) cooler
Gate245
Q:9.9e-010
From Page 2
Refrigerant ignition (R_in LgLk)
Gate222
Q:9.2e-011
Small leak (R_in SmLk)
Gate234
Q:4.6e-010
From Page 8
Refrigerant in flammable concentration range
Gate223
Q:3.5e-008
Ignition source present (R_in LgLk)
Gate225
Q:2.6e-003
From Page 9
2 repeats
3 repeats
5 repeats
Line rupture occurs (R_in LgLk)
Event105
Q:1e-006
Insufficient ventilation (kitchen)
Event224
Q:5e-002
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001



Unit is a walk in (W_in) cooler
Gate245
To Page 1
Q:9.9e-010
Leak indoors
Gate246
Leak in outside condenser
Gate308
Q:9.3e-010
Q:6e-011
From Page 3
Refrigerant ignition, large leak (W_in, LgLk)
Gate627
Refrigerant ignition (W_in SmLk)
Gate267
Q:1.6e-010
Q:7.8e-010
From Page 5
Refrigerant ignition inside cooler (W_in, LgLk)
Gate628
Refrigerant ignition in kitchen (W_in, LgLk)
Gate629
Q:4.6e-015
Q:1.6e-010
From Page 7
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Refrigerant in flammable concentration range
Gate658
Q:9.4e-006
Sufficient electrical spark present
Gate631
Q:5.2e-010
3 repeats
Line rupture occurs (W_in, LgLk)
Event140
Q:1e-005
3 repeats
Insufficient ventilation (walk in interior)
Event953
Q:9.9e-001
3 repeats
Leak is not noticed in time/no mitigation (W_in)
Event954
Q:9.5e-001
3 repeats
Spark occurs
Event957
Q:2.6e-003
3 repeats
Spark has sufficient energy
Event958
Q:1e-002
3 repeats
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)
Event959
Q:2e-001
3 repeats
Spark occurs when flammable concentration present (all scenarios)
Event960
Q:1e-004


Leak in outside condenser
Gate308
Q:6e-011
To Page 2
Feed through ignition event
Gate672
Q:5.4e-011
From Page 4
Non-feed through ignition event (Outs LgLk)
Gate676
Q:1.7e-013
Non-feed through ignition event (Outs SmLk)
Gate702
Q:5.7e-012
Refrigerant in flammable concentration range
Gate310
Q:1.8e-006
Ignition source present (Outs Lg Lk)
Gate311
Q:9.5e-006
7 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002
Refrigerant in flammable concentration range
Gate703
Q:8e-005
Ignition source present (Outs SmLk)
Gate704
Q:7.1e-006
7 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002
1 repeat
Line rupture occurs (Outs LgLk)
Event170
Q:1e-004
8 repeats
No wind
Event172
Q:6e-002
7 repeats
Blower off (outside condenser)
Event173
Q:3e-001
4 repeats
Leak is not noticed in time/no mitigation (outside)
Event174
Q:9.9e-001
Sufficient non-feed through spark present
Gate312
Q:9.5e-006
Open flame not relevant for outdoor scenarios
Gate313
1 repeat
Line rupture occurs (Outs SmLk)
Event1132
Q:4.5e-003
8 repeats
No wind
Event172
Q:6e-002
7 repeats
Blower off (outside condenser)
Event173
Q:3e-001
4 repeats
Leak is not noticed in time/no mitigation (outside)
Event174
Q:9.9e-001
Sufficient non-feed through spark present
Gate705
Q:7.1e-006
Open flame not relevant for outdoor scenarios
Gate706
4 repeats
Spark occurs with sufficient energy (condenser)
Event178
Q:9.5e-001
1 repeat
Spark occurs in flammable concentration area (Outs LgLk)
Event1070
Q:1e+000
4 repeats
Spark occurs when flammable concentration present (condenser)
Event913
Q:1e-001
4 repeats
Box around electronics does not prevent flame propagation to rest of refrigerant
Event834
Q:1e-004
4 repeats
Spark occurs with sufficient energy (condenser)
Event178
Q:9.5e-001
2 repeats
Spark occurs in flammable concentration area (Outs SmLk)
Event179
Q:7.5e-001
4 repeats
Spark occurs when flammable concentration present (condenser)
Event913
Q:1e-001
4 repeats
Box around electronics does not prevent flame propagation to rest of refrigerant
Event834
Q:1e-004

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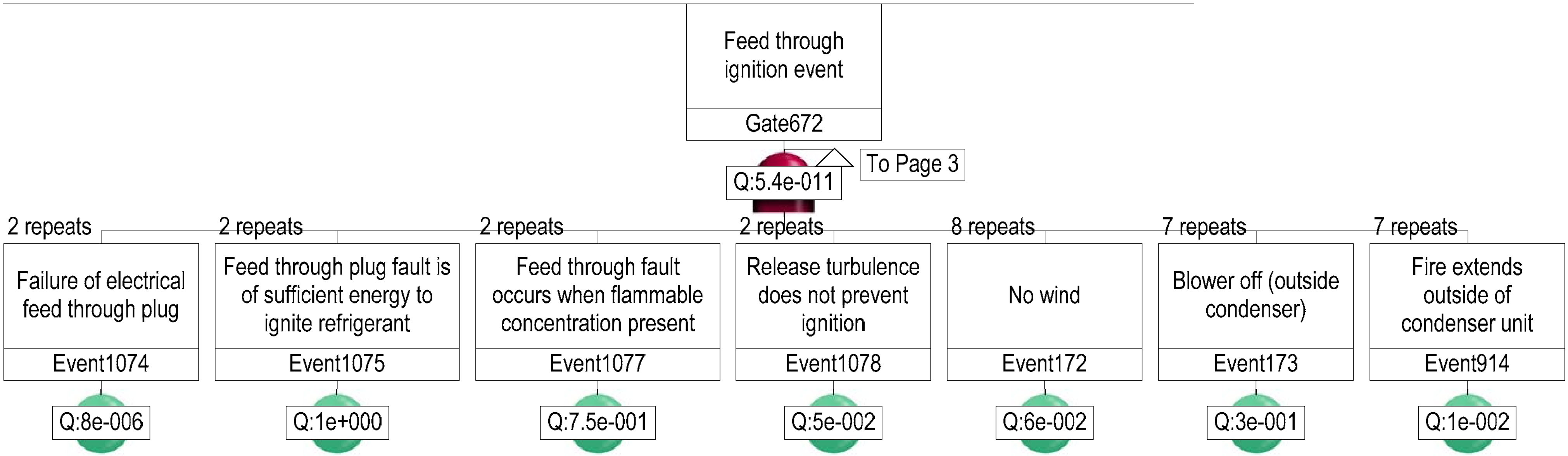
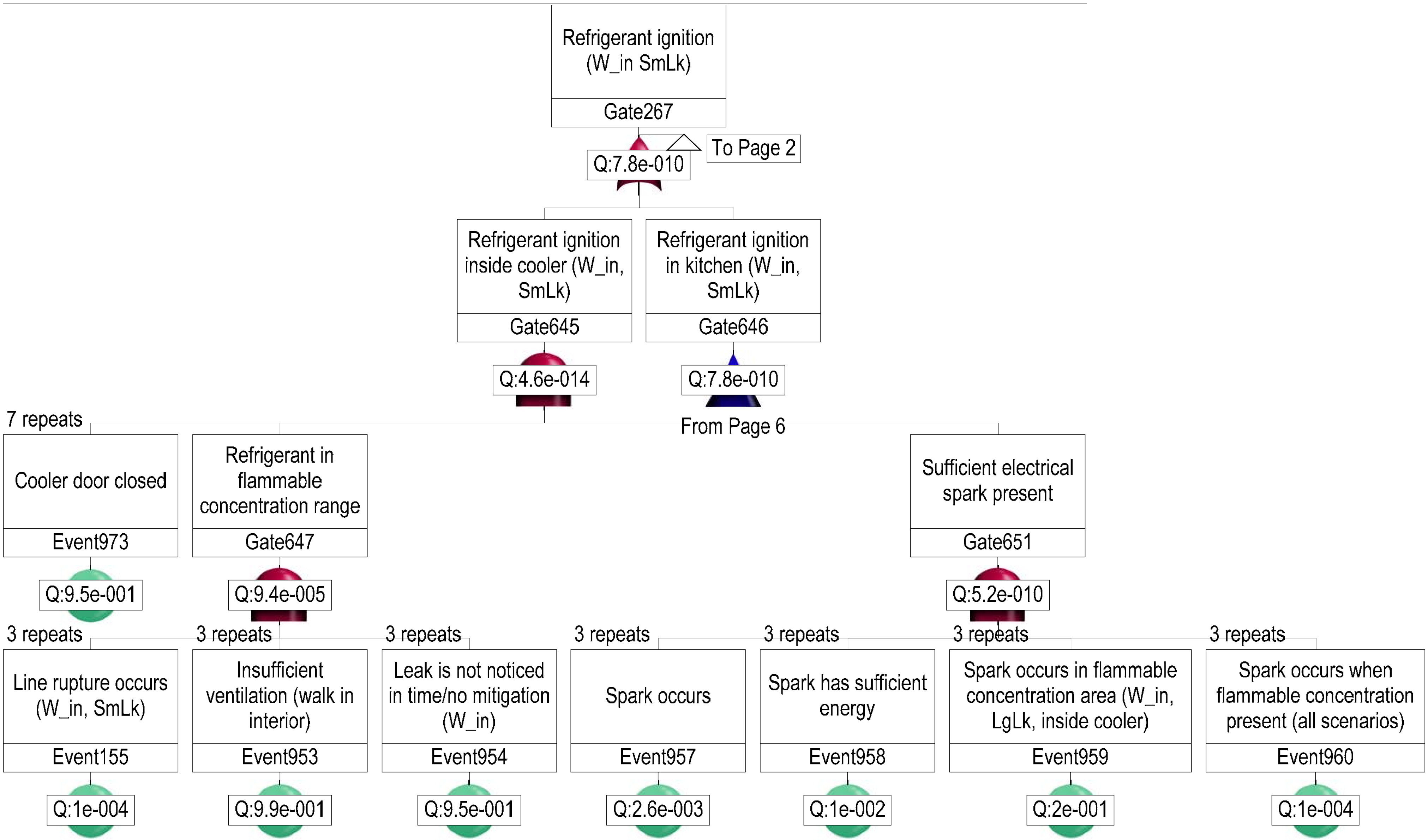
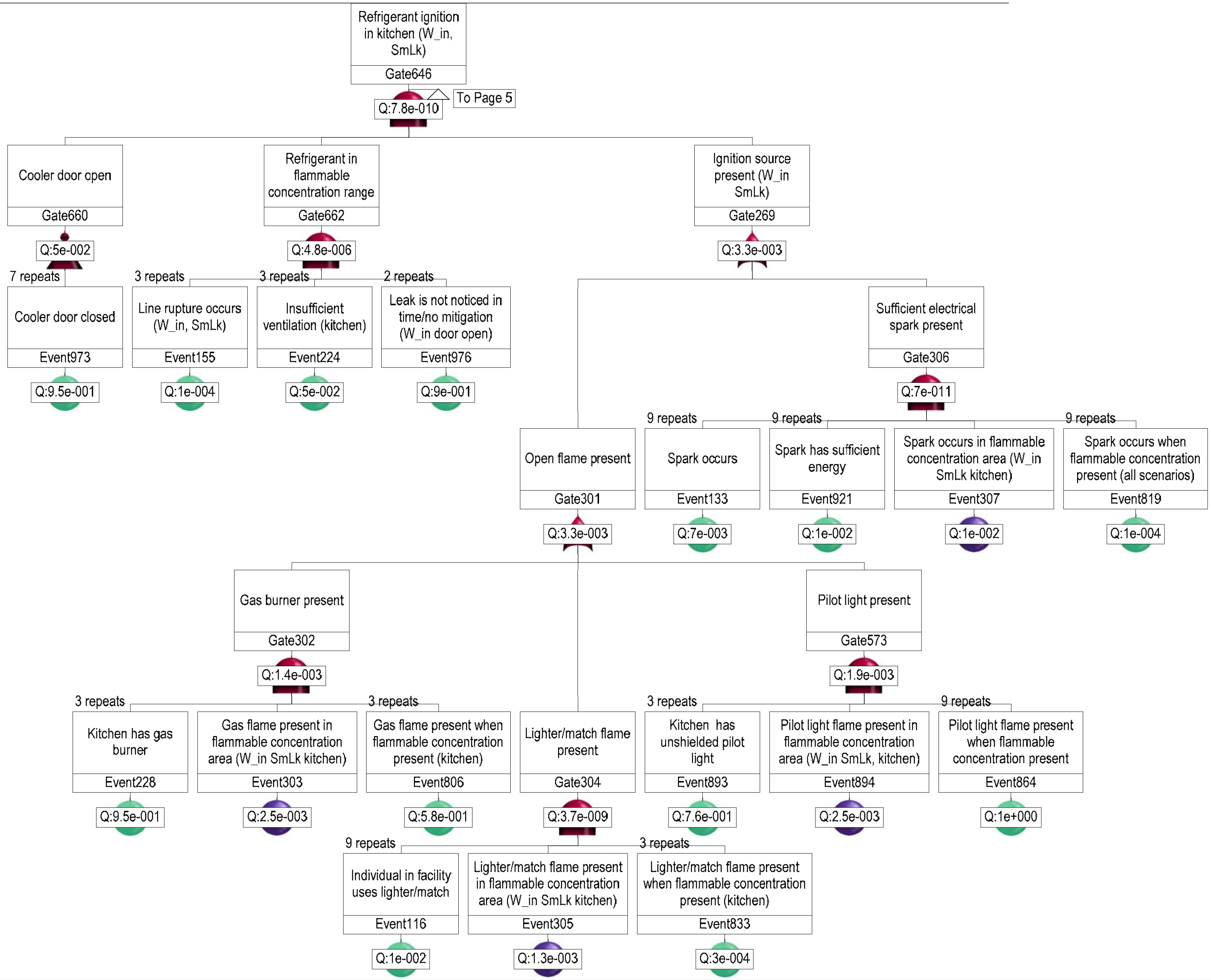
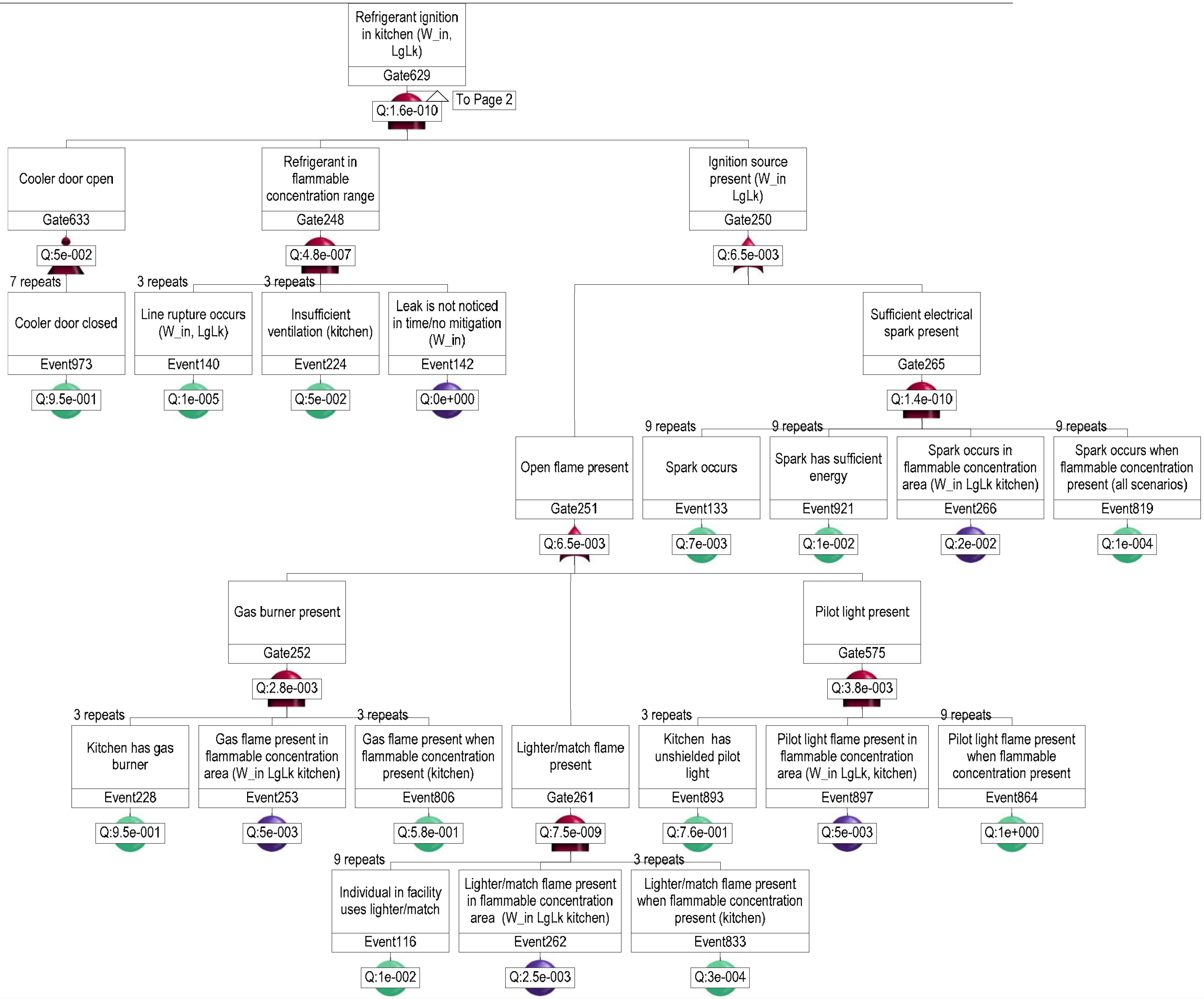
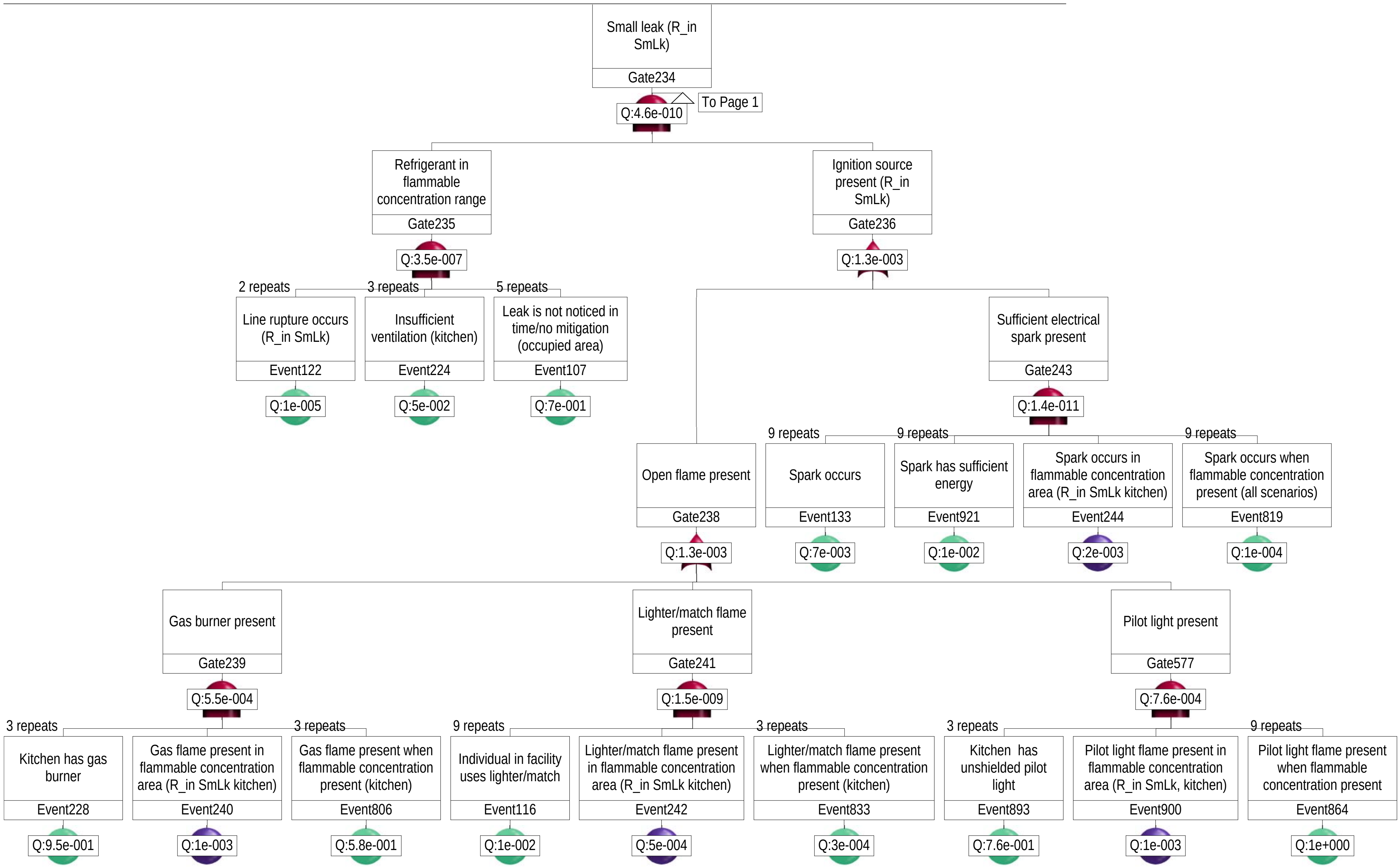

Feed through ignition event
Gate672
Q:5.4e-011
To Page 3
2 repeats
Failure of electrical feed through plug
Event1074
Q:8e-006
2 repeats
Feed through plug fault is of sufficient energy to ignite refrigerant
Event1075
Q:1e+000
2 repeats
Feed through fault occurs when flammable concentration present
Event1077
Q:7.5e-001
2 repeats
Release turbulence does not prevent ignition
Event1078
Q:5e-002
8 repeats
No wind
Event172
Q:6e-002
7 repeats
Blower off (outside condenser)
Event173
Q:3e-001
7 repeats
Fire extends outside of condenser unit
Event914
Q:1e-002

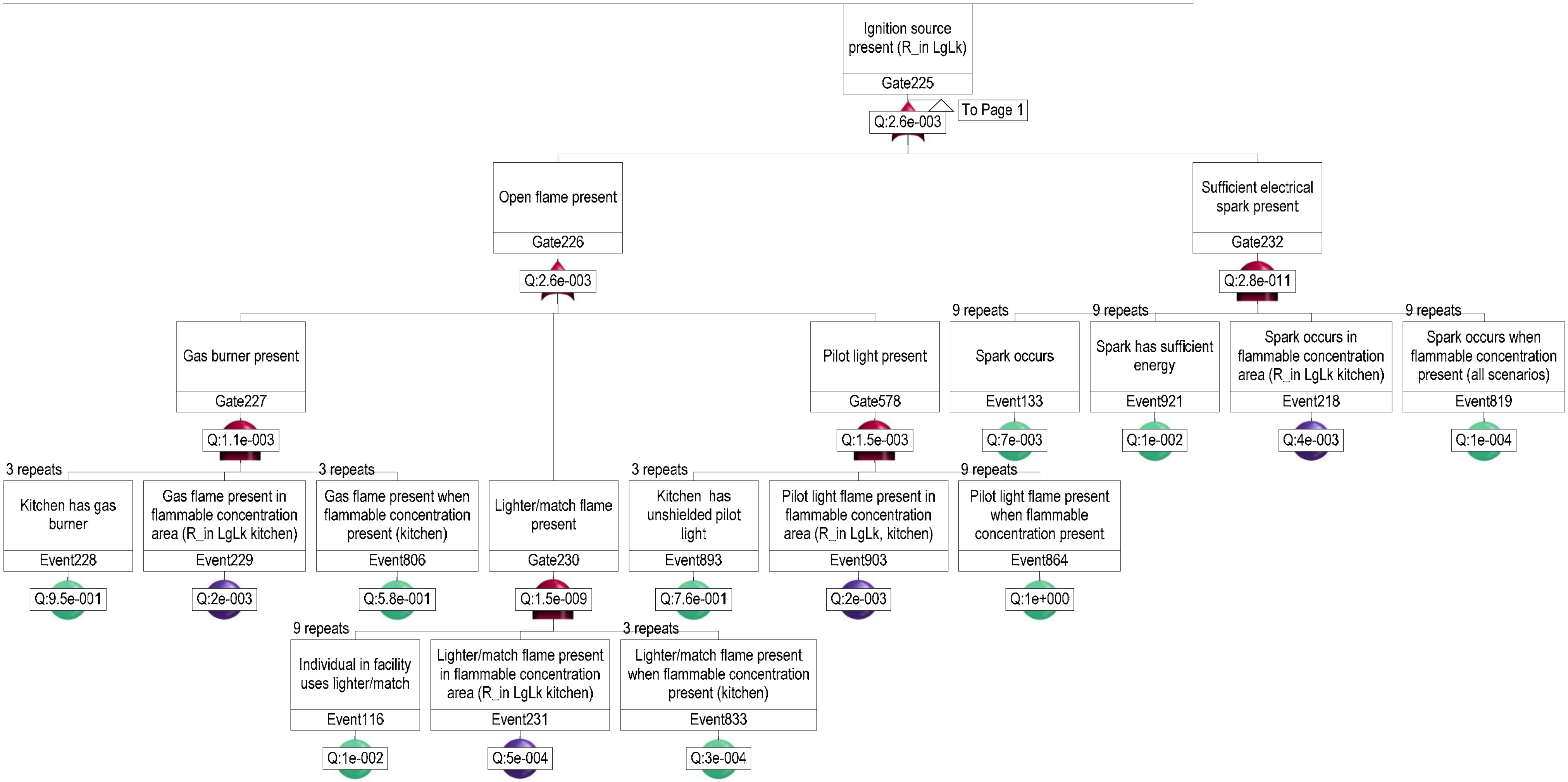

Refrigerant ignition (W_in SmLk)
Gate267
Q:7.8e-010
To Page 2
Refrigerant ignition inside cooler (W_in, SmLk)
Gate645
Q:4.6e-014
Refrigerant ignition in kitchen (W_in, SmLk)
Gate646
Q:7.8e-010
From Page 6
7 repeats
Cooler door closed
Event973
Q:9.5e-001
Refrigerant in flammable concentration range
Gate647
Q:9.4e-005
Sufficient electrical spark present
Gate651
Q:5.2e-010
3 repeats
Line rupture occurs (W_in, SmLk)
Event155
Q:1e-004
3 repeats
Insufficient ventilation (walk in interior)
Event953
Q:9.9e-001
3 repeats
Leak is not noticed in time/no mitigation (W_in)
Event954
Q:9.5e-001
3 repeats
Spark occurs
Event957
Q:2.6e-003
3 repeats
Spark has sufficient energy
Event958
Q:1e-002
3 repeats
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)
Event959
Q:2e-001
3 repeats
Spark occurs when flammable concentration present (all scenarios)
Event960
Q:1e-004

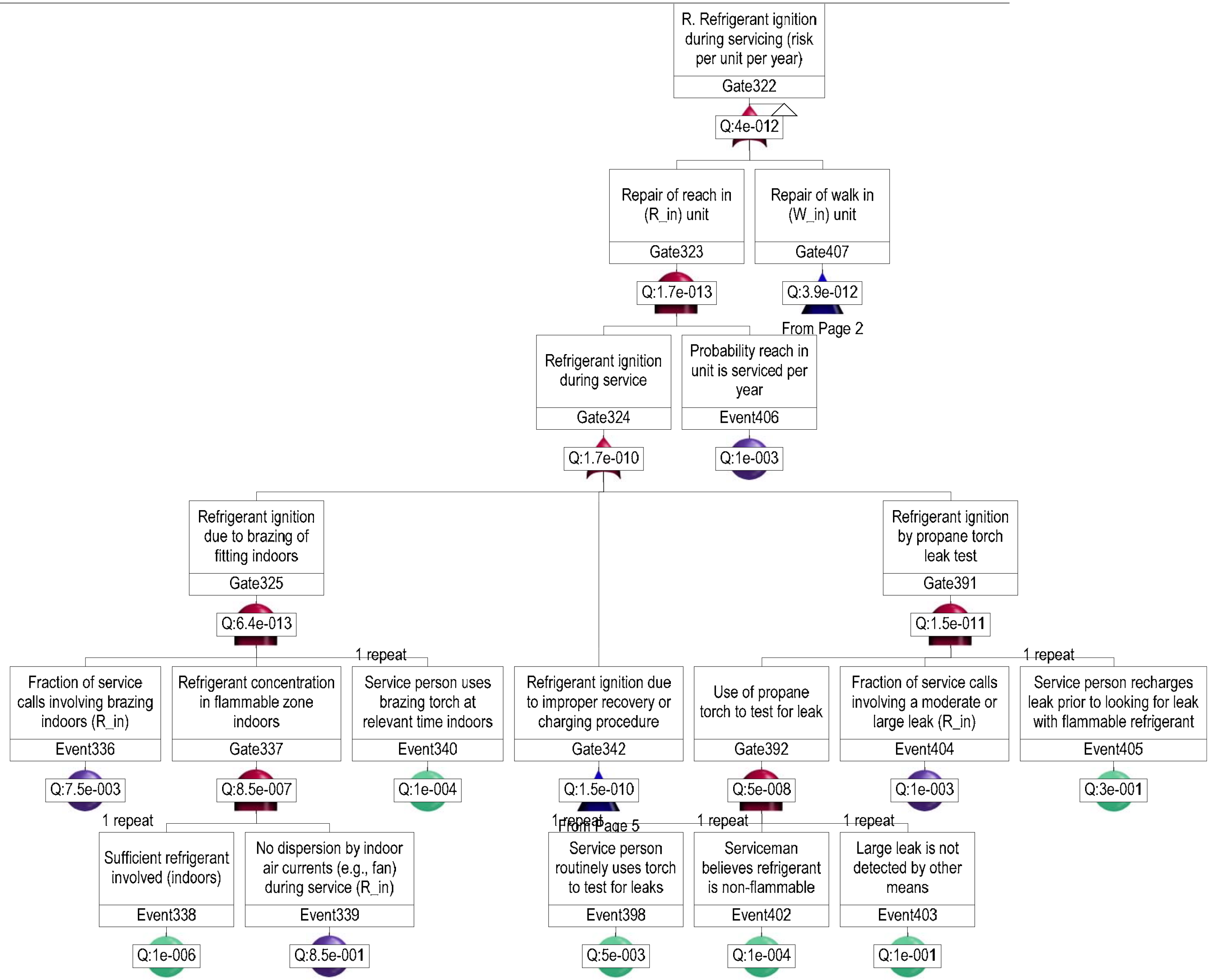

Refrigerant ignition in kitchen (W_in, SmLk)
Gate646
Q:7.8e-010
To Page 5
Cooler door open
Gate660
Q:5e-002
Refrigerant in flammable concentration range
Gate662
Q:4.8e-006
Ignition source present (W_in SmLk)
Gate269
Q:3.3e-003
7 repeats
Cooler door closed
Event973
Q:9.5e-001
3 repeats
Line rupture occurs (W_in, SmLk)
Event155
Q:1e-004
3 repeats
Insufficient ventilation (kitchen)
Event224
Q:5e-002
2 repeats
Leak is not noticed in time/no mitigation (W_in door open)
Event976
Q:9e-001
Sufficient electrical spark present
Gate306
Q:7e-011
Open flame present
Gate301
Q:3.3e-003
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (W_in SmLk kitchen)
Event307
Q:1e-002
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate302
Q:1.4e-003
Pilot light present
Gate573
Q:1.9e-003
3 repeats
Kitchen has gas burner
Event228
Q:9.5e-001
Gas flame present in flammable concentration area (W_in SmLk kitchen)
Event303
Q:2.5e-003
3 repeats
Gas flame present when flammable concentration present (kitchen)
Event806
Q:5.8e-001
Lighter/match flame present
Gate304
Q:3.7e-009
3 repeats
Kitchen has unshielded pilot light
Event893
Q:7.6e-001
Pilot light flame present in flammable concentration area (W_in SmLk, kitchen)
Event894
Q:2.5e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (W_in SmLk kitchen)
Event305
Q:1.3e-003
3 repeats
Lighter/match flame present when flammable concentration present (kitchen)
Event833
Q:3e-004

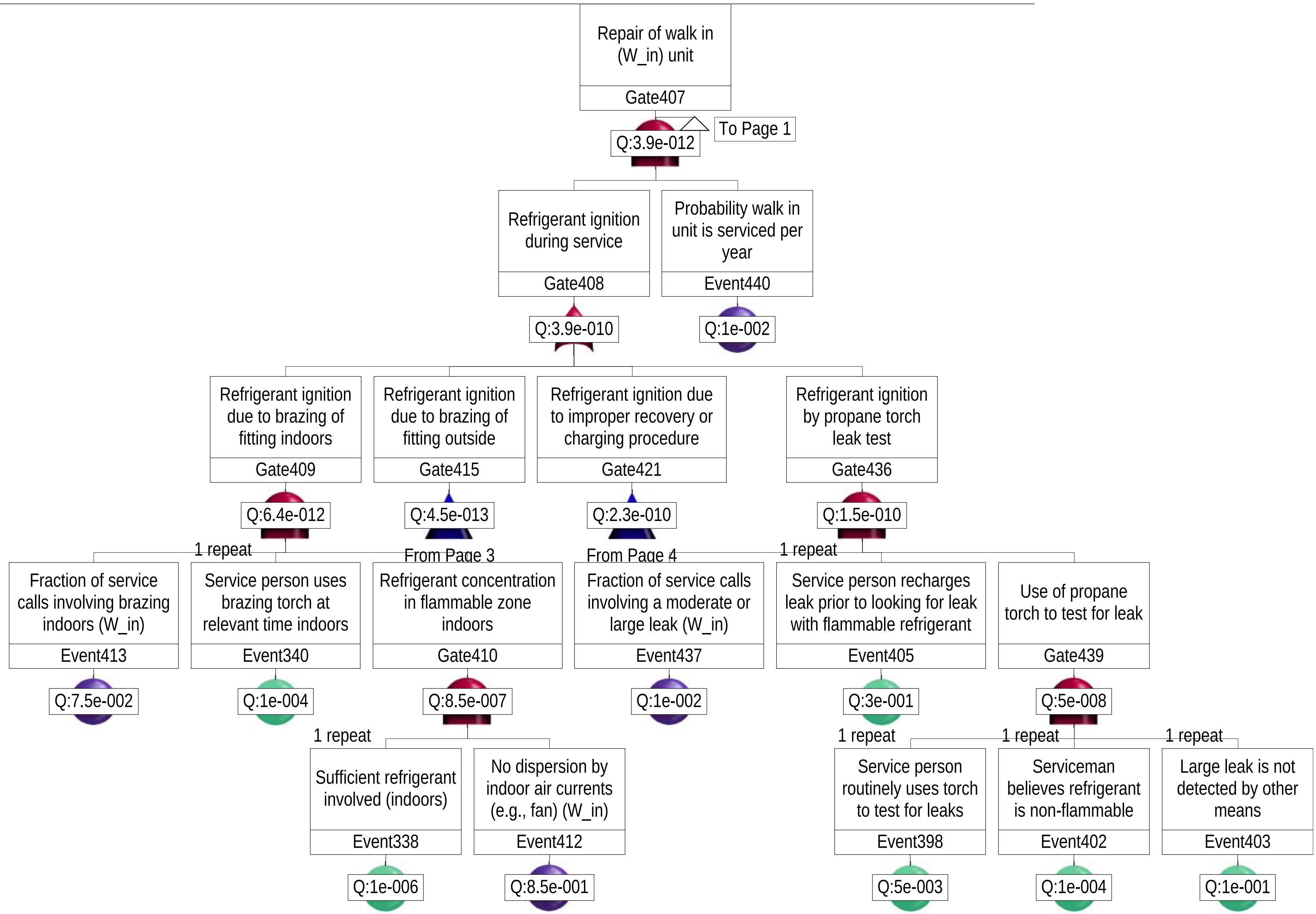

Refrigerant ignition in kitchen (W_in, LgLk)
Gate629
Q:1.6e-010
To Page 2
Cooler door open
Gate633
Q:5e-002
Refrigerant in flammable concentration range
Gate248
Q:4.8e-007
Ignition source present (W_in LgLk)
Gate250
Q:6.5e-003
7 repeats
Cooler door closed
Event973
Q:9.5e-001
3 repeats
Line rupture occurs (W_in, LgLk)
Event140
Q:1e-005
3 repeats
Insufficient ventilation (kitchen)
Event224
Q:5e-002
Leak is not noticed in time/no mitigation (W_in)
Event142
Q:0e+000
Sufficient electrical spark present
Gate265
Q:1.4e-010
Open flame present
Gate251
Q:6.5e-003
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (W_in LgLk kitchen)
Event266
Q:2e-002
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate252
Q:2.8e-003
Pilot light present
Gate575
Q:3.8e-003
3 repeats
Kitchen has gas burner
Event228
Q:9.5e-001
Gas flame present in flammable concentration area (W_in LgLk kitchen)
Event253
Q:5e-003
3 repeats
Gas flame present when flammable concentration present (kitchen)
Event806
Q:5.8e-001
Lighter/match flame present
Gate261
Q:7.5e-009
3 repeats
Kitchen has unshielded pilot light
Event893
Q:7.6e-001
Pilot light flame present in flammable concentration area (W_in LgLk, kitchen)
Event897
Q:5e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (W_in LgLk kitchen)
Event262
Q:2.5e-003
3 repeats
Lighter/match flame present when flammable concentration present (kitchen)
Event833
Q:3e-004

GRADIENT

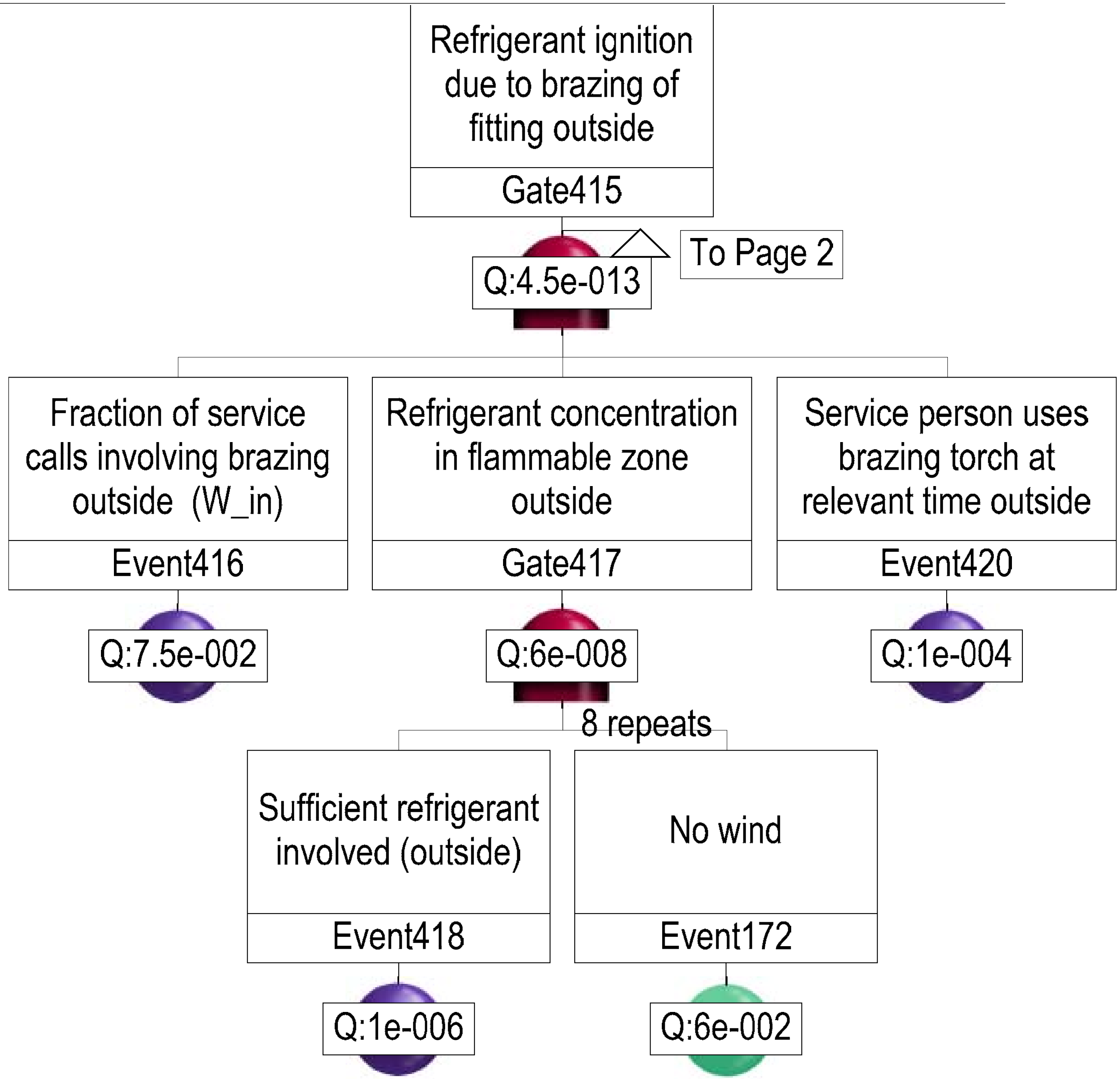

Small leak (R_in SmLk)
Gate234
Q:4.6e-010
To Page 1
Refrigerant in flammable concentration range
Gate235
Q:3.5e-007
Ignition source present (R_in SmLk)
Gate236
Q:1.3e-003
2 repeats
3 repeats
5 repeats
Line rupture occurs (R_in SmLk)
Event122
Q:1e-005
Insufficient ventilation (kitchen)
Event224
Q:5e-002
Leak is not noticed in time/no mitigation (occupied area)
Event107
Q:7e-001
Sufficient electrical spark present
Gate243
Q:1.4e-011
9 repeats
9 repeats
9 repeats
Open flame present
Gate238
Q:1.3e-003
Spark occurs
Event133
Q:7e-003
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (R_in SmLk kitchen)
Event244
Q:2e-003
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
Gas burner present
Gate239
Q:5.5e-004
Lighter/match flame present
Gate241
Q:1.5e-009
Pilot light present
Gate577
Q:7.6e-004
3 repeats
3 repeats
9 repeats
3 repeats
3 repeats
9 repeats
Kitchen has gas burner
Event228
Q:9.5e-001
Gas flame present in flammable concentration area (R_in SmLk kitchen)
Event240
Q:1e-003
Gas flame present when flammable concentration present (kitchen)
Event806
Q:5.8e-001
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in SmLk kitchen)
Event242
Q:5e-004
Lighter/match flame present when flammable concentration present (kitchen)
Event833
Q:3e-004
Kitchen has unshielded pilot light
Event893
Q:7.6e-001
Pilot light flame present in flammable concentration area (R_in SmLk, kitchen)
Event900
Q:1e-003
Pilot light flame present when flammable concentration present
Event864
Q:1e+000

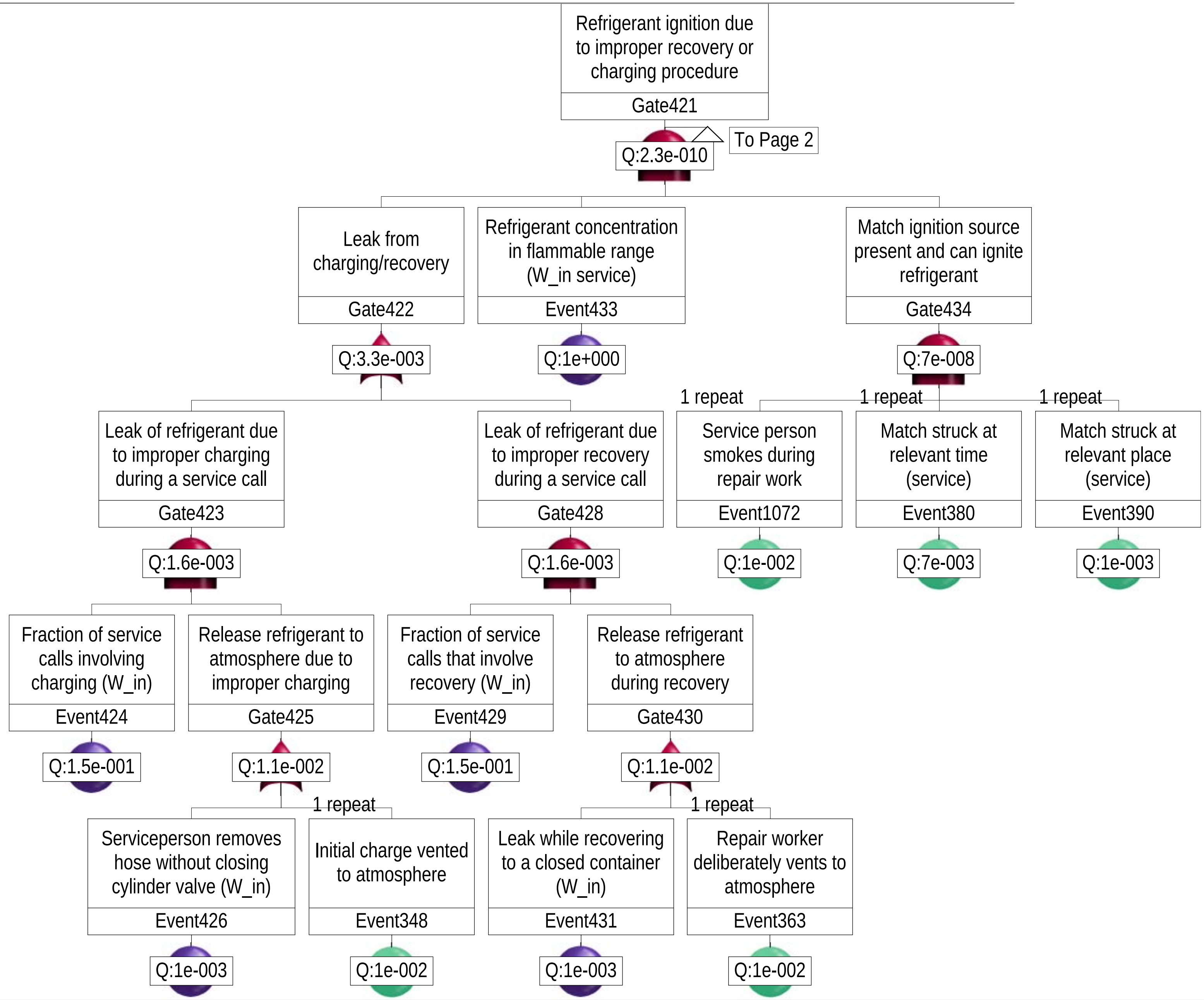

Ignition source present (R_in LgLk)
Gate225
Q:2.6e-003
To Page 1
Open flame present
Gate226
Q:2.6e-003
Sufficient electrical spark present
Gate232
Q:2.8e-011
Gas burner present
Gate227
Q:1.1e-003
Pilot light present
Gate578
Q:1.5e-003
9 repeats
Spark occurs
Event133
Q:7e-003
9 repeats
Spark has sufficient energy
Event921
Q:1e-002
Spark occurs in flammable concentration area (R_in LgLk kitchen)
Event218
Q:4e-003
9 repeats
Spark occurs when flammable concentration present (all scenarios)
Event819
Q:1e-004
3 repeats
Kitchen has gas burner
Event228
Q:9.5e-001
Gas flame present in flammable concentration area (R_in LgLk kitchen)
Event229
Q:2e-003
3 repeats
Gas flame present when flammable concentration present (kitchen)
Event806
Q:5.8e-001
Lighter/match flame present
Gate230
Q:1.5e-009
3 repeats
Kitchen has unshielded pilot light
Event893
Q:7.6e-001
Pilot light flame present in flammable concentration area (R_in LgLk, kitchen)
Event903
Q:2e-003
9 repeats
Pilot light flame present when flammable concentration present
Event864
Q:1e+000
9 repeats
Individual in facility uses lighter/match
Event116
Q:1e-002
Lighter/match flame present in flammable concentration area (R_in LgLk kitchen)
Event231
Q:5e-004
3 repeats
Lighter/match flame present when flammable concentration present (kitchen)
Event833
Q:3e-004

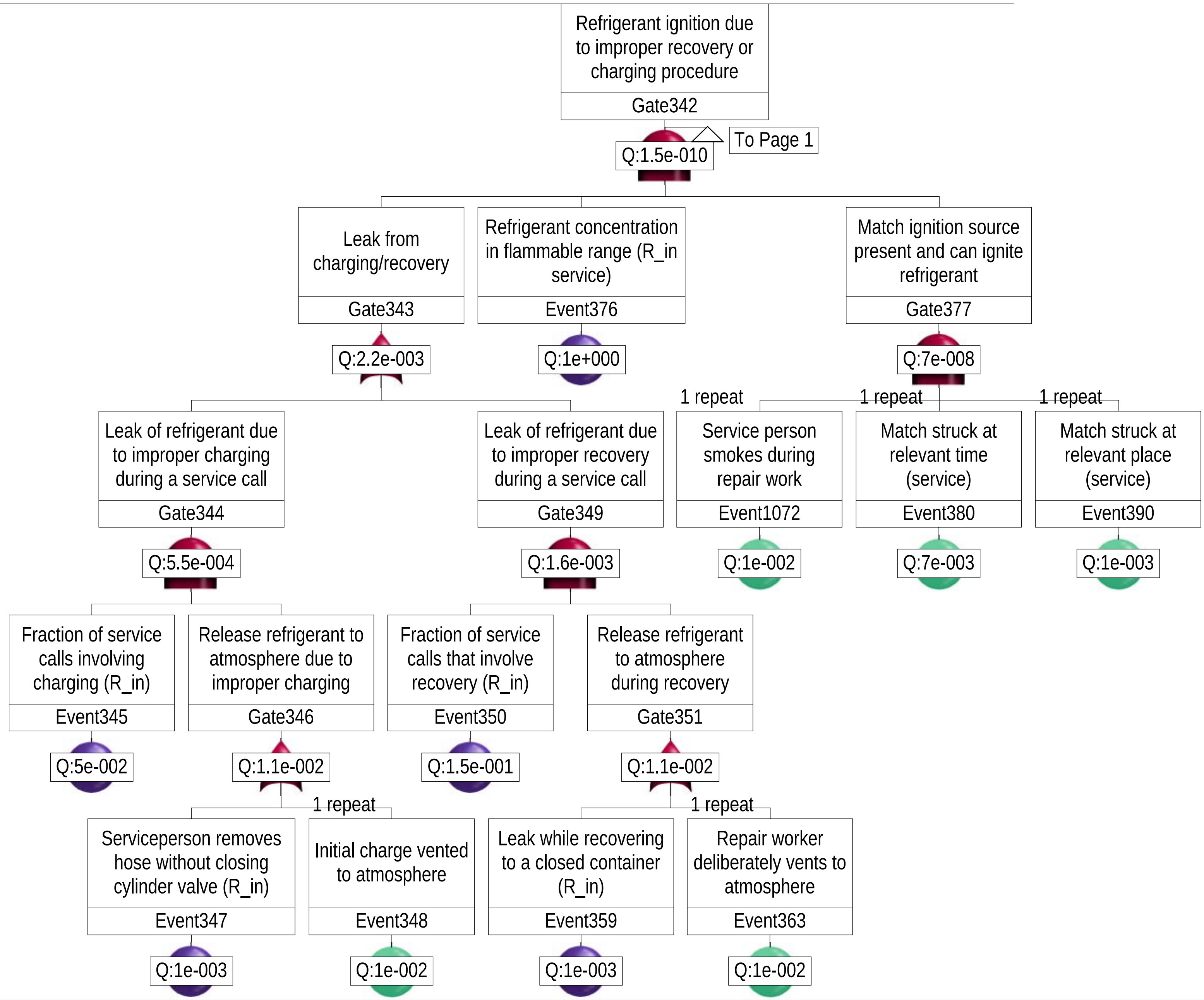

R. Refrigerant ignition during servicing (risk per unit per year)
Gate322
Q:4e-012
Repair of reach in (R_in) unit
Gate323
Q:1.7e-013
Repair of walk in (W_in) unit
Gate407
Q:3.9e-012
From Page 2
Refrigerant ignition during service
Gate324
Q:1.7e-010
Probability reach in unit is serviced per year
Event406
Q:1e-003
Refrigerant ignition due to brazing of fitting indoors
Gate325
Q:6.4e-013
Refrigerant ignition by propane torch leak test
Gate391
Q:1.5e-011
1 repeat
Fraction of service calls involving brazing indoors (R_in)
Event336
Q:7.5e-003
Refrigerant concentration in flammable zone indoors
Gate337
Q:8.5e-007
Service person uses brazing torch at relevant time indoors
Event340
Q:1e-004
Refrigerant ignition due to improper recovery or charging procedure
Gate342
Q:1.5e-010
From Page 5
Use of propane torch to test for leak
Gate392
Q:5e-008
Fraction of service calls involving a moderate or large leak (R_in)
Event404
Q:1e-003
1 repeat
Service person recharges leak prior to looking for leak with flammable refrigerant
Event405
Q:3e-001
1 repeat
Sufficient refrigerant involved (indoors)
Event338
Q:1e-006
No dispersion by indoor air currents (e.g., fan) during service (R_in)
Event339
Q:8.5e-001
1 repeat
Service person routinely uses torch to test for leaks
Event398
Q:5e-003
1 repeat
Serviceman believes refrigerant is non-flammable
Event402
Q:1e-004
1 repeat
Large leak is not detected by other means
Event403
Q:1e-001


Repair of walk in (W_in) unit
Gate407
Q:3.9e-012
To Page 1
Refrigerant ignition during service
Gate408
Q:3.9e-010
Probability walk in unit is serviced per year
Event440
Q:1e-002
Refrigerant ignition due to brazing of fitting indoors
Gate409
Q:6.4e-012
Refrigerant ignition due to brazing of fitting outside
Gate415
Q:4.5e-013
From Page 3
Refrigerant ignition due to improper recovery or charging procedure
Gate421
Q:2.3e-010
From Page 4
Refrigerant ignition by propane torch leak test
Gate436
Q:1.5e-010
1 repeat
Fraction of service calls involving brazing indoors (W_in)
Event413
Q:7.5e-002
Service person uses brazing torch at relevant time indoors
Event340
Q:1e-004
Refrigerant concentration in flammable zone indoors
Gate410
Q:8.5e-007
Fraction of service calls involving a moderate or large leak (W_in)
Event437
Q:1e-002
1 repeat
Service person recharges leak prior to looking for leak with flammable refrigerant
Event405
Q:3e-001
Use of propane torch to test for leak
Gate439
Q:5e-008
1 repeat
Sufficient refrigerant involved (indoors)
Event338
Q:1e-006
No dispersion by indoor air currents (e.g., fan) (W_in)
Event412
Q:8.5e-001
1 repeat
Service person routinely uses torch to test for leaks
Event398
Q:5e-003
1 repeat
Serviceman believes refrigerant is non-flammable
Event402
Q:1e-004
1 repeat
Large leak is not detected by other means
Event403
Q:1e-001

GRADIENT


Refrigerant ignition due to brazing of fitting outside
Gate415
Q:4.5e-013
To Page 2
Fraction of service calls involving brazing outside (W_in)
Event416
Q:7.5e-002
Refrigerant concentration in flammable zone outside
Gate417
Q:6e-008
8 repeats
Service person uses brazing torch at relevant time outside
Event420
Q:1e-004
Sufficient refrigerant involved (outside)
Event418
Q:1e-006
No wind
Event172
Q:6e-002


Refrigerant ignition due to improper recovery or charging procedure
Gate421
Q:2.3e-010
To Page 2
Leak from charging/recovery
Gate422
Q:3.3e-003
Refrigerant concentration in flammable range (W_in service)
Event433
Q:1e+000
Match ignition source present and can ignite refrigerant
Gate434
Q:7e-008
Leak of refrigerant due to improper charging during a service call
Gate423
Q:1.6e-003
Leak of refrigerant due to improper recovery during a service call
Gate428
Q:1.6e-003
1 repeat
Service person smokes during repair work
Event1072
Q:1e-002
1 repeat
Match struck at relevant time (service)
Event380
Q:7e-003
1 repeat
Match struck at relevant place (service)
Event390
Q:1e-003
Fraction of service calls involving charging (W_in)
Event424
Q:1.5e-001
Release refrigerant to atmosphere due to improper charging
Gate425
Q:1.1e-002
Fraction of service calls that involve recovery (W_in)
Event429
Q:1.5e-001
Release refrigerant to atmosphere during recovery
Gate430
Q:1.1e-002
Serviceperson removes hose without closing cylinder valve (W_in)
Event426
Q:1e-003
1 repeat
Initial charge vented to atmosphere
Event348
Q:1e-002
Leak while recovering to a closed container (W_in)
Event431
Q:1e-003
1 repeat
Repair worker deliberately vents to atmosphere
Event363
Q:1e-002


Refrigerant ignition due to improper recovery or charging procedure
Gate342
Q:1.5e-010
To Page 1
Leak from charging/recovery
Gate343
Q:2.2e-003
Refrigerant concentration in flammable range (R_in service)
Event376
Q:1e+000
Match ignition source present and can ignite refrigerant
Gate377
Q:7e-008
Leak of refrigerant due to improper charging during a service call
Gate344
Q:5.5e-004
Leak of refrigerant due to improper recovery during a service call
Gate349
Q:1.6e-003
1 repeat
Service person smokes during repair work
Event1072
Q:1e-002
1 repeat
Match struck at relevant time (service)
Event380
Q:7e-003
1 repeat
Match struck at relevant place (service)
Event390
Q:1e-003
Fraction of service calls involving charging (R_in)
Event345
Q:5e-002
Release refrigerant to atmosphere due to improper charging
Gate346
Q:1.1e-002
Fraction of service calls that involve recovery (R_in)
Event350
Q:1.5e-001
Release refrigerant to atmosphere during recovery
Gate351
Q:1.1e-002
Serviceperson removes hose without closing cylinder valve (R_in)
Event347
Q:1e-003
1 repeat
Initial charge vented to atmosphere
Event348
Q:1e-002
Leak while recovering to a closed container (R_in)
Event359
Q:1e-003
1 repeat
Repair worker deliberately vents to atmosphere
Event363
Q:1e-002

INPUT VALUES FOR FAULT TREES

Description	Event No.	R-1234ze(E)	R-1234yf	R-32	Remarks	Tree
Blower off (outside condenser)	173	0.3			It is assumed that the blower operates 30% of the time the unit is in use. Walk-in units cycle on and off all day but run longer when warm material has been placed inside and doors have been opened. Overnight, if the unit is not entered, the unit may not cycle on at all.	31
Box around electronics does not prevent flame propagation to rest of refrigerant	834	1.00E-04			Requires the motor casing to be poorly designed, defective or that it has been incorrectly removed (i.e., the basic human error probability, 1E-3). Lowered to 1E-4 assuming the box is redesigned for use with 2L refrigerants, has a warning label not to remove, etc.	
Conv str has gas burner	147	0.1			A gas burner in a convenience store is fairly unlikely. Not all convenience stores have the capacity to make food to order, many have only microwaves or no food heating equipment. They might also prefer electric cooking elements which do not require the added expense of gas service. Not all areas of the US have gas service.	1
Conv str has unshielded pilot light	862	0.05			A pilot light in a convenience store is fairly unlikely. This could be present on a gas stove (pilot lights are increasinly unlikely in residential type stoves which might be found in a small convenience store) or possibly on another appliance (e.g., a gas water heater). Not all areas of the US have gas service. For many utilities, the pilot light is shielded by a flame arrestor which would prevent flame propagation. Only this this arrestor is removed or gamaged would there be an ignition risk. The likelihood of this is less than the likelihood of a stove with an unshielded pilot light. A value of 5% (0.05) is used, half the value that a gas burner is present, accounting for the fact that many gas stove have spark igniters rather than pilot lights.	1
Cooler door closed	973	0.95			The cooler door will be closed except for periods of maintenance or, potentially, when large amounts of material are being brought into the cooler. Brief opening to allow someone to enter the cooler would not be sufficient for enough of a release to leak out and reach flammable concentrations in the kitchen.	
Factor to account for impact of humidity on R-1234zeE flammability (kitchen)	1069	0.2	NA	NA	High humidity is a modifier of the temperature effect on 1234ze(E) ignition. It may be that at temperatures less than 90F if humidity is high, refrigerant ignition is possible. However, high humidity at low temperature is not a risk. Therefore humidity is a modifying factor rather than an independent event that can produce ignition in the absence of high temperature. Relex FaultTree does not allow event values >1 so the value of event 826 is effectively doubled using this input and an OR gate. The value is higher for a kitchen due to the potential for high humidity due to dishwashers and other steam generating activities.	

Shading indicates values that are identical to the value already listed for the input in question.

Factor to account for impact of humidity on R-1234zeE flammability (kitchen)	950	0.2	NA	NA	High humidity is a modifier of the temperature effect on 1234ze(E) ignition. It may be that at temperatures less than 90F if humidity is high, refrigerant ignition is possible. However, high humidity at low temperature is not a risk. Therefore humidity is a modifying factor rather than an independent event that can produce ignition in the absence of high temperature. Relex FaultTree does not allow event values >1 so the value of event 826 is effectively doubled using this input and an OR gate. The value is higher for a kitchen due to the potential for high humidity due to dishwashers and other steam generating activities.	
Factor to account for impact of humidity on R-1234zeE flammability (Service)	944	0.03	NA	NA	High humidity is a modifier of the temperature effect on 1234ze(E) ignition. It may be that at temperatures less than 90F if humidity is high, refrigerant ignition is possible. However, high humidity at low temperature is not a risk. Therefore humidity is a modifying factor rather than an independent event that can produce ignition in the absence of high temperature. Relex FaultTree does not allow event values >1 so the value of event 438 is effectively increased by 50% using this input and an OR gate.	
Factor to account for increased flammability at high absolute humidity	1060	0.1	NA	NA	High humidity is a modifier of the temperature effect on 1234ze(E) ignition. It may be that at temperatures less than 90F if humidity is high, refrigerant ignition is possible. However, high humidity at low temperature is not a risk. Therefore humidity is a modifying factor rather than an independent event that can produce ignition in the absence of high temperature. Relex FaultTree does not allow event values >1 so the value of the adjacent temperature input is effectively doubled using this input and an OR gate.	
Factor to address impact of absolute humidity on 1234zeE flammability	933	0.0015	NA	NA	High absolute humidity is a modifier of the temperature effect on 1234ze(E) ignition. It may be that at temperatures less than 90F if humidity is high, refrigerant ignition is possible. However, high humidity at low temperature is not a risk. Therefore humidity is a modifying factor rather than an independent event that can produce ignition in the absence of high temperature. Relex FaultTree does not allow event values >1 so the value of event 109 is effectively increased by 50% using this input and an OR gate.	
Failure of electrical feed through plug	1074	8.00E-06			RIAC NPRD (2011) database failure rate for electrical feed through connectors was 4E-5/year. An operating time of 20% was assumed, resulting in a failure rate of 8.0E-6 per unit per year.	
Feed through fault occurs when flammable concentration present	1077	0.75			The feed through plug failure may not necessarily occur when the refrigerant is in the flammable range. When first released, the refrigerant will likely be above the flammable limit and by the time the refrigerant reaches the flammable range, it is possible the plug may have been cooled by the refrigerant.	
Feed through plug fault is of sufficient energy to ignite refrigerant	1075	1			A feed through plug fault was determined to have sufficient energy to ignite all 3 refrigerants.	

Fire extends outside of condenser unit	914	0.01			A refrigerant ignition event in the condenser unit itself would pose little risk for individuals or property. The concern would be whether the ignition can propagate beyond the exterior of the condenser. CFD modeling of the condenser suggests this is unlikely, even when the condenser is enclosed in a 4 walled structure. A value of 1% is applied.	
Fraction of service calls involving a moderate or large leak (R_in)	404	0.001			Based on Goetzler et al. (1998) data for heat pumps. Reach-in unit probability is lower than the value for a Walk-In unit because reach-ins are factory assembled and do not require on-site installation.	R
Fraction of service calls involving a moderate or large leak (W_in)	437	0.01			Based on Goetzler et al. (1998) data for heat pumps. Considered to be an appropriate surrogate for a walk-in unit because both are installed on site and could have custom connections that might produce leaks.	R
Fraction of service calls involving brazing indoors (R_in)	336	0.0075			The probability was set one order of magnitude lower than the walk-in value. Not all reach-in units have parts that require brazing (e.g., some now have cassettes). This is expected to increase in the future.	R
Fraction of service calls involving brazing indoors (W_in)	413	0.075			Goetzler et al. gave a figure of 0.15 for all brazing based on ADL proprietary data. Divided in half to obtain the indoor value. Heat pump data would be appropriate for walk-in case.	R
Fraction of service calls involving brazing outside (W_in)	416	0.075			Goetzler et al. gave a figure of 0.15 for all brazing based on ADL proprietary data. Divided in half to obtain the indoor value. Heat pump data would be an appropriate surrogate for a walk-in cooler case.	R
Fraction of service calls involving charging (R_in)	345	0.05			Expert opinion indicates that reach-in units will leak refrigerant less than walk-in units and so they would have lower likelihood of needing charging.	R
Fraction of service calls involving charging (W_in)	424	0.15			Goetzler et al. proprietary data for heat pump systems. Heat pump data would be appropriate for the walk-in case.	R
Fraction of service calls that involve recovery (R_in)	350	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
Fraction of service calls that involve recovery (W_in)	429	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
Gas flame present in flammable concentration area (R_in LgLk kitchen)	229	0.002			Value is 5 times lower than the analogous value for the walk in unit because the refrigerant charge is substantially less. However, the reach in unit may be somewhat more likely to be located near cooking sources than a walk in unit.	3

Gas flame present in flammable concentration area (R_in LgLk, Conv str)	113	0.001			CFD modeling shows that flammable concentrations were never reached in the convenience store. Refrigerant concentrations were in the range of 1% or less, which is far below the LFLs. The probability for this input is not zero because a very highly congested space (e.g., a very cramped store) could result in higher concentrations (due to a smaller free air space). However, such very packed spaces would be less functional and potentially less appealing to customers (and might be less likely to have food preparation service). Thus, a situation where the space was so congested that the LFL could be produced from a reach in unit leak in an area where a gas flame would be present would be an extreme situation. For example, only 1 in 1000 stores might be so heavily congested. Value = 1E-3	1
Gas flame present in flammable concentration area (R_in LgLk, Lun ctr)	197	0.001			CFD modeling shows that flammable concentrations were never reached in the lunch counter. Refrigerant concentrations were in the range of 1% or less, which is far below the LFLs. The probability for this input is not zero because a very highly congested space could result in higher concentrations (due to a smaller free air space). However, such a congested space would be less functional and less attractive to customers. It might also violate local health codes. The lunch counter modeled was also relatively small. Thus, a situation where the space was so congested that the LFL could be produced in an area where a gas flame would be present would be an extreme situation. For example, only 1 in 1000 lunch counters might be so congested such that R-32 reaches the LFL at the location of the flame source (which would commonly be located away from the cooler to mimize the work of the cooling system). Value = 1E-3	2
Gas flame present in flammable concentration area (R_in SmLk kitchen)	240	0.001			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	3
Gas flame present in flammable concentration area (R_in SmLk, Conv str)	127	5.00E-04			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	1
Gas flame present in flammable concentration area (R_in SmLk, Lun ctr)	209	5.00E-04			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	2

Gas flame present in flammable concentration area (W_in LgLk kitchen)	253	0.005			CFD modeling shows that flammable concentrations were never reached in the restaurant kitchen scenario that was modeled. With the door open, modeled R-32 concentrations were less than 4% and R-1234zeE concentrations were less than 2%, which are far below the LFLs. The probability for this input is not zero because a very highly congested space (e.g., a very crowded kitchen) could result in higher concentrations (due to a smaller free air space). However, such very packed spaces would be less functional, may violate health codes and could be hazardous to employees (e.g., kitchens should have discrete work stations with ample counter space for food preparation). The kitchen modeled was also relatively small. Thus, a situation where the space was so congested that the LFL could be produced in an area where a gas flame would be present would be an extreme situation. For example, only 1 in 200 restaurants might be so congested and configured so that R-32 reaches its LFL near a flame source (i.e., not at ground level). Value = 5E-3	3
Gas flame present in flammable concentration area (W_in SmLk kitchen)	303	0.0025			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	3
Gas flame present in flammable concentration area (W_in, LgLk, Conv str)	148	0.0013			Although a large leak from a walk in unit in the convenience store was not modeled, the values determined for the reach-in unit were so low (<1%) as to suggest that even with the larger charge volume of a walk in unit, the LFL would not be reached. Note that the convenience store modeled with a reach-in unit was fairly small and would not readily accommodate a walk-in unit and leave room for other merchandise. The value used is 4 times less than that used for the restaurant kitchen scenario because modeled refrigerant concentrations were substantially lower in the convenience store.	1
Gas flame present in flammable concentration area (W_in, SmLk, Conv str)	160	6.30E-04			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	1
Gas flame present when flammable concentration present (Conv str)	807	0.25			In a convenience store, the gas burner/stove will not be in continuous operation. We assumed that gas burner is only operated for 2 hours each around breakfast, lunch and dinner times (e.g., for preparation of foods such as soups, stews, etc.) Assuming the leak can occur any time during the day, this yields a probability of 0.25 (6 hr/24 hr). It is also assumed, based on CFD modeling, that the size of the leak has a relatively negligible impact on this input; the probability the flame source is present is the more dominant factor.	1

Gas flame present when flammable concentration present (kitchen)	806	0.58			In a restaurant kitchen, the gas burner/stove will not be in continuous operation. We assumed that gas burner is operated 85% of the time the restaurant is staffed (conservatively assumed to be 16 hours, e.g. 8am to midnight). This would include preparation times outside of the typical breakfast, lunch and dinner hours but not times when kitchen cleaning is occurring. Assuming the leak can occur any time during the day, this yields a probability of 0.58 (14 hr/24 hr). It is also assumed, based on CFD modeling, that the size of the leak has a relatively negligible impact on this input; the probability the flame source is present is the more dominant factor.	3
Gas flame present when flammable concentration present (Lun ctr)	210	0.25			In a lunch counter, the gas burner/stove will not be in continuous operation. We assumed that gas burner is only operated for 3 hours each around breakfast and lunch times (e.g., to include time for preparation of foods such as soups, stews, etc.) Assuming the leak can occur at any time of the day yields a value of 0.25 (i.e., 6 hrs/24 hrs). It is also assumed, based on CFD modeling, that the size of the leak has a relatively negligible impact on this input; the probability the flame source is present is the more dominant factor.	2
Individual in facility uses lighter/match	116	0.01			For employees/customers in relevant area. Only 20% of the population smokes, so the value can be no greater than 0.2. However, there are regulations against smoking in public spaces in many US jurisdictions (and regulations banning smoking in restaurants in many more). Note that the timing and location of the match/lighter use are addressed elsewhere.	321
Indoor temperature sufficient for 1234ze to be flammable (Service)	438	0.05	NA	NA	It is unlikely that temperatures inside a commercial building would exceed 90F (32C). Even in a kitchen, temperatures will be lower during service than during operation. A value of 0.05 is used but may be overly conservative.	R
Indoor temperature sufficient for 1234zeE to be flammable (kitchen area)	826	0.2	NA	NA	Temperatures in the kitchen could reach 90°F, particularly in the summer, although efforts will be made to control the temperature for staff comfort. A value of 0.2 is used to be conservative.	3
Indoor temperature sufficient for 1234zeE to be flammable (lun ctr/conv str)	1003	0.003	NA	NA	The temperature would need to be above approximately 90F. This would be very unlikely in such a facility. It would have to occur only during period of extreme outdoor temperature and the facility would have to have no functioning air conditioning. In areas with long periods of high temperatures (e.g. the desert Southwest) facilities without air conditioning would be even less likely. Assume high outdoor temps greater than 90F would occur, on average, 20 days per year (14/365 = 0.055). Assume only 1 in 20 facilities would have no air conditioning or air conditioning that wasn't working during these times (0.055/20 = 0.003)	21
Initial charge vented to atmosphere	348	0.01		0.05	Goetzler et al. used 0.05. However, flammability and price will be motivating factors that change behavior. Less a factor for R-32 than for R-1234yf and R-1234ze(E).	R

Insufficient ventilation (conv store)	108	0.25			A convenience store will have an HVAC system for heating and cooling that will be on most of the time, although the blower will not always be operating. Opening and closing of the entry door and customer movement will also produce air currents in the facility. The units themselves have fans which induce air flow and would help to dilute the refrigerant, particularly if there are multiple units per facility.	1
Insufficient ventilation (kitchen)	224	0.05			A kitchen would likely have good ventilation to control both heat and cooking odors. The ventilation would more likely be operating when cooking is occurring and more ignition sources are present. Ventilation could be off during slow periods but ignition sources would be less likely during this time frame.	3
Insufficient ventilation (Lun ctr)	192	0.2			Due to its small size, the lunch counter might not have good ventilation, although some ventilation near the cooking area would be likely. There are also code requirements for ventilation in public spaces.	2
Insufficient ventilation (walk-in interior)	953	0.99			It will be assumed that inside the cooler ventillation will not be sufficient to disperse the refrigerant to concentrations below the LFL. Because the evaporator is near the ceiling, any air moving equipment may increase the likelihood of a flammable concentration near the spark ignition source.	1
Kitchen has gas burner	228	0.95			Gas burners in kitchens are very likely because they allow cooks to more carefully control heat compared to electric burners. Induction burners are another option which allows rapid control of heat without a flame source. Not all areas of the US have gas service.	3
Kitchen has unshielded pilot light	893	0.76			A pilot light in a kitchen could be present on a gas stove (research shows that pilot lights are very common on commerical ranges compared to residential ranges) or possibly on another appliance (e.g., a gas water heater, although this may not be located in a kitchen). Not all areas of the US have gas service. For many utilities, the pilot light is shielded by a flame arrestor which would prevent flame propagation. Only if this arrestor is removed or damaged would there be an ignition risk. The likelihood of this is less than the likelihood of a stove with an unshielded pilot light. A value of 0.76 is used, 80% the value that a gas burner is present, accounting for the fact that some gas stoves will have spark igniters rather than pilot lights.	1
Large leak is not detected by other means	403	0.1			Even if the service person normally uses a propane torch to test for leaks (an increasingly rare practice) he/she may use other methods first.	R
Leak is not noticed in time/no mitigation (occupied area)	107	0.7			Largely depends on whether leak is audible, although oil spray from a large leak might be visible. Reach-in units would be occupied spaces so someone is likely to be present when the facility is open. However a leak may not be noticed due to other equipment noise, or a lack of proximity of an individual to the leak location.	321

Leak is not noticed in time/no mitigation (outside)	174	0.99			The condenser is typically placed in an out of the way place where individuals are unlikely to be present. Due to outdoor noise (e.g., traffic) an individual not next to condenser would not hear a leak. It is also unlikely that if they heard a noise they would take any action, particularly if they were not an employee.	31
Leak is not noticed in time/no mitigation (W_in door open)	142	0.9			If the walk-in door is open, a leak might be detected but this would be less likely than with a reach in unit because any audible sound or oil spray would be shielded by the walk in unit walls.	31
Leak is not noticed in time/no mitigation (W_in)	954	0.95			Walk-in units would only be occupied on a limited basis. A leak would not be recognized if someone wasn't actually in the unit, which would be quite infrequent.	31
Leak while recovering to a closed container (R_in)	359	0.001			Typical probability associated with human error.	R
Leak while recovering to a closed container (W_in)	431	0.001			Typical probability value associated with human error because the individual will have made an error in recovery connections.	R
Lighter/match flame present in flammable concentration area (W_in LgLk kitchen)	262	0.0025			CFD modeling shows that flammable concentrations were never reached in the restaurant kitchen scenario that was modeled. With the door open, modeled R-32 concentrations were less than 4% and R-1234zeE concentrations were less than 2% which are far below the LFLs. The probability for this input is not zero because a very highly congested space (e.g., a very crowded kitchen) could result in higher concentrations (due to a smaller free air space). However, such very packed spaces would be less functional, may violate health codes and could be hazardous to employees (e.g., kitchens should have discrete work stations with ample counter space for food preparation). The kitchen modeled was also relatively small. Thus, a situation where the space was so congested so the refrigerant reaches its LFL in an area where a smoking related ignition source was present (typically several feet above the floor surface) would be an extreme situation. For example, only 1 in 400 kitchens might be so congested. This value is 2 fold lower than the equivalent value for a non-smoking flame due to the relative height where a smoking source would occur.	3
Lighter/match flame present in flammable concentration area (R_in LgLk kitchen)	231	5.00E-04			Value is 5 times lower than the analogous value for the walk in unit because the refrigerant charge is substantially less. However, the reach in unit may be somewhat more likely to be located near cooking sources than a walk in unit.	3

Lighter/match flame present in flammable concentration area (R_in LgLk, Conv str)	117	5.00E-04			CFD modeling shows that flammable concentrations were never reached in the convenience store scenario that was modeled. Refrigerant concentrations never exceeded 1%. The probability for this input is not zero because a very highly congested space (e.g., a very crowded store) could result in higher concentrations (due to a smaller free air space). However, such very packed spaces would be less functional and unappealing to customers (and potentially less likely to have food service). Thus, a situation where the space was so congested so the refrigerant reaches its LFL in an area where a smoking related ignition source was present (typically several feet above the floor surface) would be an extreme situation. This value is 2 fold lower than the equivalent value for a non-smoking flame due to the relative height where a smoking source would occur.	1
Lighter/match flame present in flammable concentration area (R_in LgLk, Lun ctr)	199	5.00E-04			CFD modeling shows that flammable concentrations were never reached in the lunch counter scenario that was modeled. Modeled concentrations were less than 1% which is far below the LFL of R-32, R-1234yf or R-1234ze(E). The probability is not zero because a very highly lunch counter (with limited free air space) with a cigarette lighting source located in the worst-case location could pose a risk. This would however be a highly extreme situation, particularly for a lunch counter vs a convenience store where a congested space with dissuade patrons. For example, only 1 in 2000 lunch counters might be so congested that R-32 reaches its LFL where a match or lighter might be in use (modeling does show that the refrigerant released from the top of the unit does spread out across the room at approximately 6 feet in height before sinking towards the floor).	2
Lighter/match flame present in flammable concentration area (R_in SmLk kitchen)	242	5.00E-04			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	3
Lighter/match flame present in flammable concentration area (R_in SmLk, Conv str)	129	3.80E-04			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	1
Lighter/match flame present in flammable concentration area (R_in SmLk, Lun ctr)	212	2.50E-04			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	2
Lighter/match flame present in flammable concentration area (W_in SmLk kitchen)	305	0.0013			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	3

Lighter/match flame present in flammable concentration area (W_in, LgLk, Conv str)	150	6.30E-04			Although a large leak from a walk in unit in the convenience store was not modeled, the values determined for the reach-in unit were so low (<1%) as to suggest that even with the larger discharge volume of a walk in unit, the LFL would not be reached. Note that the convenience store modeled with a reach-in unit was fairly small and would not readily accommodate a walk-in unit and leave room for other merchandise. This value is 2 fold lower than the equivalent value for a non-smoking flame due to the relative height where a smoking source would occur.	1
Lighter/match flame present in flammable concentration area (W_in, SmLk, Conv str)	162	3.10E-04			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	1
Lighter/match flame present when flammable concentration present (Conv str)	818	0.01			A match take 5 seconds to strike and light a cigarette. A butane lighter would be similar. A cigarette takes about 5 minutes to smoke. We can assume that workers will not smoke inside the small facility due to employer restrictions. Patrons may smoke in localities where this is not prohibited. Assuming one smoker is always present in the store during key hours of operation (8am to 10 pm, 14 hours total), there will be 168 lighting events comprising a total of 840 seconds. When divided by the total number of hours per day (assuming the leak could occur at any time), the resulting value is 0.01 (840 seconds = 0.23 hr; 0.23 hr/24 hr = 0.01). Note this scenario elsewhere assumes no ventilation which may not be compatible with prolonged smoking in the facility.	1
Lighter/match flame present when flammable concentration present (kitchen)	833	3.00E-04			We can assume that workers will not smoke inside the kichen or walk-in cooler during operating hours due to employer restrictions to limit the impacts on food flavor and the air of the adjoining dining room. Smoking in the dining room is not relevant because CFD modeling shows flammable refrigerant concentrations will not be produced there. Smoking in the kitchen might occur in 'down hours' when the restaurant is fairly empty and the kitchen is inactive. This smoking activity might occur for 30 minutes per day. Of that time, only 30 seconds may be spent actually lighting the cigarette (5 seconds per cigarette x 6 cigarettes per 30 minutes). Out of a total 24 hour day when the leak might occur, this represents a probability of 3E-4 ([0.5 min /60 min per hr]/24 hr. Note this scenario elsewhere assumes no ventilation which may not be compatible with prolonged smoking in the facility.	3

Lighter/match flame present when flammable concentration present (Lun ctr)	824	0.003			A match take 5 seconds to strike and light a cigarette. A butane lighter would be similar. A cigarette takes about 5 minutes to smoke. We can assume that workers will not smoke inside the small facility due to employer restrictions. Patrons may smoke in localities where this is not prohibited. Assuming one smoker is always present in the lunch counter during key hours of operation (around breakfast and lunch time, 4 hours total), there will be 48 lighting events comprising a total of 240 seconds. When divided by the total number of hours per day (assuming the leak could occur at any time), the resulting value is 0.003 (240 seconds = 0.07 hr; 0.07 hr/24 hr = 0.003). Note this scenario elsewhere assumes no ventilation which may not be compatible with prolonged smoking in the facility.	2
Line rupture occurs (Outs LgLk)	170	1.00E-04			Events per unit per year. Based on the likelihood of a leak from inlet piping in an air handler in a heat pump from Goetzler et al. (1998). Due to both fatigue and wear. Assumed to be a large type of leak that would be less frequent than smaller types of leaks. Large lines for an outside condenser unit might be like the large lines on a heat pump.	1
Line rupture occurs (Outs SmLk)	316	0.0045			Events per unit per per year. Based on likelihood of a leak within an air handler in a heat pump system from Goetzler et al. (1998), 4.5E-3 per year. This would include both fatigue and wear. The PMS considered that large lines for an outside condenser unit would be analogous to the large lines on a heat pump.	1
Line rupture occurs (R_in LgLk)	105	1.00E-06			Events per unit per year. Based on Ayres (2000) equipment monitoring data for catastrophic leaks as cited by Colborne and Suen (2004) at 2E-6/yr and ADL (1991) at 7E-7/yr. This would include failure due to fatigue and wear. Note that this is similar to the value reported by Unilever for the frequency of all leaks (aside from pinhole leaks) in ice cream freezers (1.4E-6 leaks per year). An Australian government report states that anecdotal information suggests that up to 10% of small to medium commercial refrigeration units could have catastrophic leaks during their 10 to 12 year lifetime which would be a leak rate on the order of 10-2 per unit per year (Brodribb and McCann, 2010). This value clearly contradicts the actual monitoring data cited above but is based on anecdotal reports.	321
Line rupture occurs (R_in SmLk)	122	1.00E-05			Events per unit per year. Based on Ayres (2000) equipment monitoring data for medium leaks as cited by Colborne and Suen (2004). Believed to include leaks caused by fatigue as well as wear. Note that a Unilever assessment of leaks of company ice cream units reported a value of 1.4E-6 leaks per year, excluding pin hole leaks. This value is 10 times higher which may be appropriate considering variation in design and differences between the reach-in cooler and ice cream freezer.	31

Line rupture occurs (W_in, LgLk)	140	1.00E-05			Events per unit per per year. Includes both fatigue and wear. Ten times higher than the value for the reach-in unit due to the variability and error inherent in on site installation of walk-in units.	31
Line rupture occurs (W_in, SmLk)	155	1.00E-04			Events per unit per per year. Ten times higher than the value for the reach-in unit due to the variability and error inherent in on site installation of walk-in units.	1
Lun ctr has gas burner	196	0.25			Although a lunch counter would very likely have heating elements for cooking, these could be electric. For the small facility considered here, electric might be preferred due to ease of installation and lower ventilation requirements. Not all areas of the US have gas service.	2
Lun Ctr has unshielded pilot light	874	0.13			A pilot light in a lunch counter could be present on a gas stove (pilot lights are increasinly unlikely in residential type stoves which might be found in a small lunch counter) or possibly on another appliance (e.g., a gas water heater). Not all areas of the US have gas service. For many utilities, the pilot light is shielded by a flame arrestor which would prevent flame propagation. Only this this arrestor is removed or damaged would there be an ignition risk. The likelihood of this is less than the likelihood of a stove with an unshielded pilot light. A value of 5% (0.13) is used, half the value that a gas burner is present, accounting for the fact that many gas stove have spark igniters rather than pilot lights.	1
Match struck at relevant place (service)	390	0.001			An element of human error is involved here because individual will have to ignore their training if they are to strike a match near the unit. Thus a typical human error rate is used.	R
Match struck at relevant time (service)	380	0.007			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 (demonstrated for yf). 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
No dispersion by indoor air currents (e.g., fan) (W_in)	412	0.85			It is assumed that if the unit is being serviced, the door to the walk in will be open and air currents in the larger facility would be relevant, although perhaps limited by narrow opening of the doorway. The value used for the reach-in case (0.85) is also used here.	R

No dispersion by indoor air currents (e.g., fan) during service (R_in)	339	0.85			This could occur if the building HVAC system is not operating during the service call or if the blower of the HVAC system is not engaged. There is no reason that such systems would be turned off for service of a cooler unit. The frequency of blower operation will be depend on the difference between exterior and interior temperatures. Assume that the blower is operating 15% of the time and is not operating 85% of the time.	R
No wind	172	0.06			Data from NOAA (undated) indicate that in the US, still air conditions prevail, on average, approximately 6% of the time. Will vary by geographic region.	31
Outdoor temperature sufficient for 1234ze to be flammable	175	0.3	NA	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 90°F, in other regions (e.g., the Northeast and Great Lakes areas) temperatures above 90°F will not occur consistently during the summer, and in other regions (e.g., the desert Southwest, Southern Texas) temperatures may be above 90°F for more than 3 months. Therefore a value of 0.3 is reasonable for a national average.	R31
Pilot light flame present in flammable concentration area (R_in LgLk, Conv str)	905	0.001			CFD modeling shows that flammable concentrations were never reached in the convenience store. Refrigerant concentrations were in the range of 1% or less, which is far below the LFLs. The probability for this input is not zero because a very highly congested space (e.g., a very cramped store) could result in higher concentrations (due to a smaller free air space). However, such very packed spaces would be less functional and potentially less appealing to customers (and might be less likely to have food preparation service). Thus, a situation where the space was so congested that the LFL could be produced from a reach in unit leak in an area where a pilot light would be present would be an extreme situation. For example, only 1 in 1000 stores might be so heavily congested. Value = 1E-3	1
Pilot light flame present in flammable concentration area (R_in LgLk, kitchen)	903	0.001			Value is the same as that for the gas flame because the pilot light and gas flame are expected to be in the same location	1
Pilot light flame present in flammable concentration area (R_in LgLk, Lun Ctr)	875	1.00E-03			CFD modeling shows that flammable concentrations were never reached in the lunch counter. Refrigerant concentrations were in the range of 1% or less, which is far below the LFLs. The probability for this input is not zero because a very highly congested space could result in higher concentrations (due to a smaller free air space). However, such a congested space would be less functional and less attractive to customers. It might also violate local health codes. The lunch counter modeled was also relatively small. Thus, a situation where the space was so congested that the LFL could be produced in an area where a pilot light would be present would be an extreme situation. For example, only 1 in 1000 lunch counters might be so congested such that R-32 reaches the LFL at the location of the flame source (which would commonly be located away from the cooler to mimize the work of the cooling system). Value = 1E-3	1

Pilot light flame present in flammable concentration area (R_in SmLk, Conv str)	906	5.00E-04			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	1
Pilot light flame present in flammable concentration area (R_in SmLk, kitchen)	900	0.001			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	1
Pilot light flame present in flammable concentration area (R_in SmLk, Lun Ctr)	878	5.00E-04	5.00E-04	5.00E-04	The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	1
Pilot light flame present in flammable concentration area (W_in LgLk, Conv str)	882	0.0013			Although a large leak from a walk in unit in the convenience store was not modeled, the values determined for the reach-in unit were so low (<1%) as to suggest that even with the larger charge volume of a walk in unit, the LFL would not be reached. Note that the convenience store modeled with a reach-in unit was fairly small and would not readily accommodate a walk-in unit and while leaving sufficient room for other merchandise. The value used is 4 times less than that used for the restaurant kitchen scenario because modeled refrigerant concentrations were substantially lower in the convenience store.	1
Pilot light flame present in flammable concentration area (W_in LgLk, kitchen)	897	0.005			CFD modeling shows that flammable concentrations were never reached in the restaurant kitchen scenario that was modeled. With the door open, modeled R-32 concentrations were less than 4% and R-1234zeE concentrations were less than 2%, which are far below the LFLs. With the cooler door closed, R-1234zeE concentrations were below 4% (R-32 not modeled). The probability for this input is not zero because a very highly congested space (e.g., a very crowded kitchenr) could result in higher concentrations (due to a smaller free air space). However, such very packed spaces would be less functional, may violate health codes and could be hazardous to employees (e.g., kitchens should have discrete work stations with ample counter space for food preparation). The kitchen modeled was also relatively small. Thus, a situation where the space was so congested that the LFL could be produced in an area where a pilot light would be present would be an extreme situation. For example, only 1 in 200 restaurants might be so congested so that R-32 reaches its LFL. Value = 5E-3	1
Pilot light flame present in flammable concentration area (W_in SmLk, Conv str)	863	6.30E-04			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	1
Pilot light flame present in flammable concentration area (W_in SmLk, kitchen)	894	0.0025			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	1
Pilot light flame present when flammable concentration present	864	1			Pilot lights by their very nature are always on.	1

Probability reach in unit is serviced per year	406	0.001			Events per unit per year. Based on Goetzler et al. (1998) data for heat pumps. Reach-in unit probability is lower than the value for a walk-in unit because reach-ins are factory assembled and do not require on-site installation.	R
Probability walk in unit is serviced per year	440	0.01			Events per unit per year. Based on Goetzler et al. (1998) data for heat pumps. Is this relevant to coolers? Walk-in unit value should be higher than reach-in value because these are installed on site so there is less quality control.	R
Refrigerant concentration in flammable range (R_in service)	376	1			Assume that the refrigerant is in the flammable range at some location if a release occurs during repair for R-1234yf and R-32 (1.0). This may be limited to the point of release. However, for R-1234zeE, which is not flammable at ambient temperatures, the value is substantially less (0.2).	R
Refrigerant concentration in flammable range (W_in service)	433	1	0.2	1	Assume that the refrigerant is in the flammable range at some location if a release occurs during repair for R-1234yf and R-32 (1.0). This may be limited to the point of release. However, for R-1234zeE, which is not flammable at ambient temperatures, the value is substantially less (0.2).	R
Release turbulence does not prevent ignition	1078	0.05		1	R-1234yf and R-1234ze(E) have very unstable flame properties; a relatively modest amount of tubulence in the jet of released refrigerant could prevent the flame being established.	
Repair worker deliberately vents to atmosphere	363	0.01		0.05	Goetzler et al. used 0.05, based on the discouraging effect of training and regulations. In the Goetzler analysis, the concern was regulatory compliance. Now the concern will be safety-related so the probability of venting will be lower. The higher price of A2L refrigerants will also encourage recovery. Less a factor for R-32 than R-1234yf or R-1234ze(E).	R
Service person recharges leak prior to looking for leak with flammable refrigerant	405	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.	R
Service person routinely uses torch to test for a leak	398	0.005			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 is available and inexpensive.	
Service person smokes during repair work	1072	0.01			Goetzler et al. used 0.05 but the value should not be lower due to the higher cost of cigarettes, less tolerance of smoking in the clients space (all of which are occupied by the members of the public) and recognition of refrigerant flammability. The value is likely still high.	R
Service person uses brazing torch at relevant time indoors	340	1.00E-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, perhaps just a few minutes. Overall, a likely value might be 0.0001	R

Service person uses brazing torch at relevant time outside	420	1.00E-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, perhaps just a few minutes. Overall, a likely value might be 0.0001	R
Serviceman believes refrigerant is non-flammable	402	1.00E-04			From the Goetzler et al. assumption for believing a system contains R-22 if the label is removed or the individual isn't paying attention. 1E-3 is a typical value for human error related events. The individual would have to ignore markings and disregard their training suggesting a value 10-fold lower is appropriate.	R
Serviceperson removes hose without closing cylinder valve (R_in)	347	0.001			Goetzler et al. typical human error rate of 1E-3.	R
Serviceperson removes hose without closing cylinder valve (W_in)	426	0.001			Typical probability associated with human error.	R
Spark has sufficient energy	921	0.01	0.01	0.1	The probability that an electrical short has sufficient energy to ignite the refrigerant must be low, particularly for R-1234yf and R-1234zeE based on their very high MIE. Assume 0.01 for R-1234yf and R-1234zeE and 0.1 for R-32.	
Spark occurs	133	0.007			For wiring/appliances. According to the US NRC, the typical failure rate for wire shorts is 3E-7 per operating hour. Assuming 10 types of equipment (or equipment plugs) are present and regularly used in the area where refrigerant is released, and each is used 25% of the time (2190 hours), yields a value of 7 E-3 per year.	321
Spark occurs in flammable concentration area (Outs LgLk)	1070	1			CFD modeling shows that the leak may only reach the LFL in the immediate vicinity of the leak. This is true even when the condenser is located in an enclosure which restricts refrigerant dispersal. However, if a spark occurred within the condenser (the only spark source contemplated here) it would likely be within the flammable concentration zone.	31
Spark occurs in flammable concentration area (Outs SmLk)	179	0.75			CFD modeling shows that the leak may only reach the LFL in the immediate vicinity of the leak. This is true even when the condenser is located in an enclosure which restricts refrigerant dispersal. However, if a spark occurred within the condenser it would likely be within the flammable concentration zone. Value is 75% of that for the large leak due to the smaller leak rate and greater potential for dispersion.	31
Spark occurs in flammable concentration area (R_in LgLk kitchen)	218	0.004			Value is 5 times lower than the analogous value for the walk in unit because the refrigerant charge is substantially less. However, the reach in unit may be somewhat more likely to be located near cooking sources than a walk in unit.	3

Spark occurs in flammable concentration area (R_in LgLk, Conv str)	119	0.002			CFD modeling shows that flammable concentrations were never reached in the convenience store. Refrigerant concentrations were in the range of 1% or less, which is far below the LFLs. The probability for this input is not zero because a very highly congested space (e.g., a very cramped store) could result in higher concentrations (due to a smaller free air space). However, such very packed spaces would be less functional and potentially less appealing to customers (and might be less likely to have food preparation service). Thus, a situation where the space was so congested that the refrigerant reached its LFL in an area where a spark source would be present would be an extreme situation. The value used is 2 times that used for the flame source because spark sources can occur at more locations in the convenience store.	1
Spark occurs in flammable concentration area (R_in LgLk, Lun ctr)	201	0.002			CFD modeling shows that flammable concentrations were never reached in the convenience store. Refrigerant concentrations were in the range of 1% or less, which is far below the LFLs. The probability for this input is not zero because a very highly congested space (e.g., a very cramped store) could result in higher concentrations (due to a smaller free air space). However, such very packed spaces would be less functional and potentially less appealing to customers (and might be less likely to have food preparation service). Thus, a situation where the space was so congested that the refrigerant reached its LFL in an area where a spark source would be present would be an extreme situation. The value used is 2 times that used for the flame source because spark sources can occur at more locations in the convenience store.	2
Spark occurs in flammable concentration area (R_in SmLk kitchen)	244	0.002			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	3
Spark occurs in flammable concentration area (R_in SmLk, Conv str)	134	0.001			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	1
Spark occurs in flammable concentration area (R_in SmLk, Lun ctr)	217	0.001			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	2

Spark occurs in flammable concentration area (W_in LgLk kitchen)	266	0.02			CFD modeling shows that flammable concentrations were never reached in the restaurant kitchen scenario that was modeled. With the door open, modeled R-32 concentrations were less than 4% and R-1234zeE concentrations were less than 2% which are far below the LFLs. The probability for this input is not zero because a very highly congested space (e.g., a very crowded kitchen) could result in higher concentrations (due to a smaller free air space). However, such very packed spaces would be less functional, may violate health codes and could be hazardous to employees (e.g., kitchens should have discrete work stations with ample counter space for food preparation). The kitchen modeled was also relatively small. Thus, a situation where the space was so congested that the LFL could be produced in an area where a spark would be present would be an extreme situation. For example, only 1 in 200 restaurants might be so congested. Note that possible spark sources may be more widely distributed in the space than flame sources and thus the value is 4 times higher than the analogous probability for flame sources. Value = 2e-2	3
Spark occurs in flammable concentration area (W_in SmLk kitchen)	307	0.01			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	3
Spark occurs in flammable concentration area (W_in, LgLk, Conv str)	152	0.005			Although a large leak from a walk in unit in the convenience store was not modeled, the values determined for the reach-in unit were so low (<1%) as to suggest that even with the larger discharge volume of a walk in unit, the LFL would not be reached. Note that the convenience store modeled with a reach-in unit was fairly small and would not readily accommodate a walk-in unit while leaving sufficient room for other merchandise. Note that possible spark sources may be more widely distributed in the space than flame sources and thus the value is 2 times higher than the analogous probability for flame sources.	1
Spark occurs in flammable concentration area (W_in, LgLk, inside cooler)	959	0.2		0.3	CFD modeling indicated that with the cooler door closed, R-1234zeE did not approach a flammable concentration. The peak concentration was approximately 4% which is well below the LFL. The probability is not zero because a very well filled cooler could have a smaller airspace and therefore less free air space. However, a very filled cooler would be less efficient and make it difficult to find items. It is likely that a very substantial reduction in free space would be required to increase peak refrigerant concentration by a factor of 50%. A value of 0.2 is used but is likely conservative.	1
Spark occurs in flammable concentration area (W_in, SmLk, Conv str)	166	0.0025			The value is half of that used for the large leak. CFD modeling suggests that a change in release rate has only a limited impact on peak refrigerant concentration.	1

Spark occurs inside cooler	957	0.0026			According to the US NRC, the typical failure rate for wire shorts is 3E-7 per operating hour. Assuming only 1 piece of electrical equipment is in the cooler (i.e., the evaporator), yields a value of 2.6E-3 per year (8760 hr/yr * 3E-7/hr).	321
Spark occurs when flammable concentration present (all scenarios)	819	1.00E-04			Sparks will be of very short duration (fractions of seconds) and can occur any time during the year. The controlling factor is the duration of time the refrigerant is in the flammable range. CFD modeling (which while not showing concentrations above the LFL can provide an indication of concentration time courses in a congested space where the LFL might be reached) suggests that the refrigerant will only be in the flammable range for a brief period of time (5 minutes). Assuming a leak duration of 5 minutes yields a probability of 1E-5 (5 minutes/525,600 minutes per year). Increase by a factor of 10 to account for the fact that multiple outlets/appliances could generate a spark. Value =1E-4	31
Spark occurs when flammable concentration present (condenser)	913	0.1			In other scenarios, sparks are not necessarily associated with the refrigerant release but could be from other equipment present. Here we are dealing with a release in the condenser which could be ignited by a spark in the condenser. The probability is therefore whether an electrical fault would co-occur with a refrigerant release (the likelihood of which is addressed elsewhere). We will assume that a spark could occur in 10% of all refrigerant release events.	
Spark occurs with sufficient energy (condenser)	178	0.95		0.99	A fan spark would have high enough energy to ignite these refrigerants in most cases, based on studies by Honeywell. The issue is whether the spark contacts the refrigerant, which depends on casing integrity and is addressed elsewhere.	31
Sufficient refrigerant involved (indoors)	338	1.00E-06			Assumes refrigerant isn't fully recovered at the start of service and is present in sufficient quantity to be flammable. 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