Final Report

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RISK ASSESSMENT OF TRANSPORT REFRIGERATION SYSTEMS USING A2L FLAMMABLE REFRIGERANTS

Final Report

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Abbreviations

ADL	Arthur D. Little, Inc.
AHRI	Air-Conditioning, Heating, & Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
FT	Fault Tree
FTA	Fault Tree Analysis
GWP	Global Warming Potential
HVAC	Heating, Ventilating, and Air Conditioning
LFL	Lower Flammability Limit
MIE	Minimum Ignition Energy
ODP	Ozone Depletion Potential
OEM	Original Equipment Manufacturer
R-1234yf	2,3,3,3-Tetrafluoropropene
R-125	Pentafluoroethane
R-134a	1,1,1,2-Tetrafluoroethane
R-143a	1,1,1-Trifluoroethane
R-152a	1,1-Difluoroethane
R-22	Chlorodifluoromethane
R-290	Propane
R-32	1,1-Difluoromethane
R-404A	Blend of R-125, R-143a, and R-134a
R-516A	Azeotropic blend of R-1234yf, R-134a, and R-152a
UFL	Upper Flammability Limit
WCF	Worst Case Formulation for Flammability
WCFF	Worst Case Fractionation for Flammability

Executive Summary

There is worldwide interest in developing substitutes for materials whose environmental release may contribute to global climate change. The primary refrigerants currently used in refrigerated transport applications include R-404A (a blend of pentafluoroethane [R-125], 1,1,1-trifluoroethane [R-143a], and 1,1,1,2-tetrafluoroethane [R-134a]), and R-134a, greenhouse gases with global warming potentials (GWPs) in excess of 1,400. Possible replacements for these refrigerants in transport applications include Safety Group A2L refrigerants (per ANSI/ASHRAE Standard 34), which have lower GWPs but also exhibit lower flammability. Although normal operation poses negligible flammability risk, accidental releases due to equipment faults, fatigue, or improper repair procedures could potentially result in refrigerant ignition. To better understand the potential risks of using A2L refrigerants in the refrigerated transport sector, Gradient conducted a risk assessment to evaluate the potential of these gases to be ignited in the case of accidental situations. Four use applications were evaluated: refrigerated shipping containers; refrigerated trucks; single compartment refrigerated trailers; and 3-compartment refrigerated trailers. The assessment included computational fluid dynamics (CFD) modeling and a fault tree analysis (FTA) to quantify ignition risks. The CFD modeling indicated that accidental releases of A2L refrigerants could produce concentrations that exceed the respective refrigerant lower flammability limits (LFLs). Incorporating these findings, the FTA estimated the risks of ignition due to accidental releases of various A2L refrigerants as up to 3×10^{-10} events per unit per year for the evaluated refrigerated transport application: 3-compartment refrigerated trailers. The impact of Safety Shutoff Valves (SSOVs) was evaluated in the risk assessment. While the highest risks of ignition were observed to be related to the time the 3-compartment trailer was being serviced, in which an SSOV system does not have an impact, the presence of an SSOV system was found to lower the risks of ignition under other operating conditions (*e.g.*, while the 3-compartment trailer was parked but not in servicing) by approximately an order of magnitude. All of the other refrigerated transport applications under consideration involved similar internal geometries (*i.e.*, generally boxes with various internal obstructions) with similar activities (*e.g.*, loading and unloading), and similar order of magnitude risks are expected for those applications. For comparison, the overall risk of a vehicle collision due to brake failure is 3×10^{-7} per vehicle operating hour. Based on CFD modeling and FTA, the risk assessment indicates that the average risks associated with the use of A2L refrigerants in the assessed applications are significantly lower than the risks of common hazard events from other sources and well below the risks commonly accepted by the public in general.

1 Introduction

Restrictions on the use of ozone-depleting substances in 1996, in accordance with the Montreal Protocol, lead to the use of hydrofluorocarbons, such as R-134a or R-404A, in various refrigeration and cooling applications in the US (US EPA, 2010a). R-134a (1,1,1,2-tetrafluoroethane) has an ozone depletion potential (ODP) of 0 but has a global warming potential (GWP) of 1,430 (IPCC-AR4, 2007).[1] R-404A is a blend of 44% R-125 (pentafluoroethane), 52% R-143a (1,1,1-trifluoroethane), and 4% R-134a. It has an ODP of 0 but a GWP of 3,922 (US EPA, 2010a). New refrigerants are being developed with zero ODP and GWPs at least 10 times lower than Montreal Protocol-era substances. The Kigali Amendment to the Montreal Protocol signed in October 2016 has added urgency to the search for alternatives to existing high-GWP chemicals used by industry. One class of potential replacement refrigerants exhibit relatively low GWPs but also low flammability: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)-34/ISO-817 Safety Group A2L refrigerants.

A number of prior risk assessments (most sponsored by AHRI) have evaluated the ignition potential and associated consequences of A2L and A3 refrigerants in stationary sector applications (AHRI, 2012, 2015; AHRTI, 2017, 2019; Hunter, 2021). In general, these have found the use of A2L refrigerants to pose acceptably low levels of risk in the context of the likelihood of other types of undesirable accident events. AHRI (2012) assessed the risk of using A2L refrigerants, including R-32 and R-1234yf, in residential split heat pump systems using both computational fluid dynamics (CFD) modeling and field-scale experiments, finding that, while flammable concentrations could be formed by accidental release of the refrigerants, the risks of ignition were significantly lower than the incidence rate of residential fires due to other causes. The same suite of refrigerants were assessed for use in commercial cooling systems in AHRI (2015), which similarly concluded that the risks of refrigerant ignition were lower than the risks of significant commercial structure fires. AHRTI (2017) performed field-scale experimental ignition testing of several refrigerants, including R-32, and found that a number of physical phenomena, including phase transitions, may complicate desktop refrigerant ignition assessments. AHRTI (2019) similarly performed field-scale experimental ignition testing for an A2L refrigerant (R-454C) and an A3 refrigerant (R-290), finding that the A2L refrigerant did not generally ignite in low-humidity air, but that the A3 refrigerant was commonly able to be ignited and led to significantly more severe ignition consequences. A1 and A2L refrigerants, including R-32, were evaluated in Hunter (2021) for how they might impact ongoing fire events; in one scenario the A2L refrigerant was observed to have greater impacts to both released heat and HF generation relative to the A1 refrigerant.

Substantially much less work appears to have been done in the refrigerated transport sector. While a number of evaluations have been published in conference proceedings, details of the supporting information are lacking and/or studies were methodologically limited (*i.e.*, lacking any modeling or measurement of refrigerant releases).

The current assessment, carried out for AHRI, considers the following use scenarios:

- Refrigerated shipping containers;
- Refrigerated trucks;

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

- Single compartment refrigerated trailers; and
- Multi-compartment refrigerated trailers.[2]

As used in the context of this evaluation, "risk" is the likelihood or probability that leaked refrigerant from one of the applications evaluated is ignited. Risks are evaluated and quantified through the process of risk assessment. The risks related to the use of A2L refrigerants were evaluated in a multi-step process. The first step in the process was to consider the possible scenarios under which a refrigerant could leak and be ignited. Data were then gathered to support a quantitative estimation of the risk associated with each potential ignition scenario. Once all of the potential scenarios were identified and the necessary data were collected, the data were 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 characteristics of several A2L refrigerants, including gathering data on the upper and lower flammability limits (UFL and LFL, respectively), the minimum ignition energy (MIE), and the fundamental burning velocity.
2. An assessment of potential refrigerant concentrations in air in the event of an accidental release in multi-compartment refrigerated trailers. CFD modeling was used to evaluate potential concentrations at different locations in the area surrounding the leak.
3. Research on the probabilities and frequencies of events contributing to accidental releases of an A2L refrigerant under different situations (*e.g.*, during loading or unloading, while mobile, during repair) and potential leak rates. When specific data were not available, values were developed based on input from scientists and engineers with expertise in the design, operation, and repair of appropriate systems.
4. Data from the previous three steps were combined to estimate overall risks of ignition through the use of fault tree analysis (FTA). The results were then considered in the context of other ignition-related risks.

The risk assessment was based on data we obtained from literature sources and reports or presentations of third-party scientists and engineers; we did not independently verify or confirm the information presented in those sources but have assumed it to be valid.

[2] The risk assessment does not address the risks of particular product designs, but rather evaluates the use of refrigerants in the general applications described in Table 2.2.

2 Data Acquisition

2.1 Information Gathering

2.1.1 Literature Review

We conducted a broad literature review to identify any prior risk assessments of flammable refrigerant use in transport scenarios and to obtain studies that might be useful for parameterizing the fault tree analysis (*i.e*., baseline probabilities of unit failures, number of units in service, operating hours) or provide comparison risks (risks of other transportation related events). The literature search involved on-line searches *via* Google using various combinations of search terms such as "refrigerant", "fire" and "NHTSA" "risk assessment", "trailer", "shipping container", "refrigerated transport" and "safety evaluation". References cited in identified documents were further explored where appropriate. The result was a table of potentially relevant information sources, which included a comment about their potential value for the current project (Appendix A). Overall, only a limited amount of information was identified. Of particular interest were US government data on vehicle collision and fire frequencies, although these data often lacked the specificity for vehicles likely to be involved in refrigerated transport (*e.g*., limited to the broad "large truck and bus" category). There was also a conference paper (Colbourne *et al*., 2017) describing risks of R290 as a refrigerant in transport systems and which provides some estimates of leak frequencies; however many of the underlying details are lacking. Another conference paper (Poolman *et al*., 2016) addressed the use of several A2L refrigerants and one A3 refrigerant in transport operations. The risk assessment apparently considered the risk of having a flammable concentration present but not the actual risk of ignition, which was considered outside the scope of the effort. Some possible approaches for mitigation of releases were discussed. Overall, the literature review provided some useful concepts and ideas to the current exercise but generally highlighted the limitations and/or lack of evaluation conducted to date.

2.1.2 Surveys and Facility Visits

Much of in the information needed for fault tree parameterization (*e.g*., frequencies of different types of system damage, behaviors of personnel during repair) are unlikely to be published and indeed, were not found in the literature review. To obtain such information, Gradient prepared a questionnaire that was provided to an individual overseeing operations at a repair center (Appendix B). After providing the questionnaire, a Gradient scientist visited the repair center to view the operations and assist the individuals in completing the questionnaire (this helped in ensuring consistent interpretation of the questions). Two facilities were visited, one in the Pacific Northwest and one in Southern California. The exact identities of the service centers are not disclosed as confidentiality was assured to encourage maximum information sharing. The California facility visit involved representatives from two nearby facilities. Attempts to schedule additional visits were unsuccessful due to the COVID pandemic and other scheduling challenges. Although the potential bias in obtaining information from only 3 facilities is a concern, a summary of the visits were provided to the AHRI PMS for review and consideration so that any non-representative information could be identified. No comments were received. The summary memo of the survey and visits is also included in Appendix B. In general, useful information was obtained regarding the frequency of types of system damage observed, the duration and other characteristics of repairs that are commonly performed, policies regarding smoking on-site, and the likelihood of possible failure mechanisms during repair. Information was generally provided as impressions or generalizations rather than as analyses of collected data (*e.g.*, there were no quantitative analyses of types of damage that are seen in a given year). The information obtained was used in developing inputs to some FT parameters and *via* the FTA parameterization process

2.2 Properties of Refrigerants

The risk assessment evaluated R-516A as a base case refrigerant with other lower GWP gases evaluated in a comparative basis. R-516A is an azeotropic blend of R-1234yf, R-134a, and R-152a, with R-1234yf comprising 77.5% of the blend (Arkema, 2016). The GWP of R-516A is 131 (Arkema, 2020a), far below that of R-134a and R-404A (US EPA, 2010a,b; IPCC, 2007).

Table 2.1 summarizes the flammability properties of R-516A, along with flammability properties for four other ASHRAE A2L gases that are also proposed for use as refrigerants in transport applications: R-1234yf, R-454A, R-454C, and R-455A. An ASHRAE Class A3 gas, propane (R-290), was also included in this evaluation as it has been used in various refrigerant applications (*e.g.*, small refrigerators in certain countries). Of particular interest is the minimum ignition energy (MIE). The spark energy of common spark plugs is in the range of 20-30 mJ (ACC, 2007). Thus, it would take a substantial ignition source (*e.g.*, a very high-energy spark, an open flame, or a very hot surface) to ignite most of the refrigerants of interest; the exception being R-290, which has an MIE well below that of spark plugs and even below that of many static sparks.

Even if ignited, the A2L refrigerants pose a limited risk of short-term flame propagation through air due to their low burning velocities.[3] By definition, Class 2L refrigerants have a measured burning velocity of less than or equal to 10 cm/second (0.3 ft/second). These low burning velocities suggests that, even if an A2L refrigerant used in a transport application were ignited, the flame could be extinguished by wind or other air currents. As shown in Table 2.1, the burning velocities of all of the refrigerants of interest are well below 10 cm/s with the exception of R-290, which has a burning velocity of 46 cm/s and would not have this potential mitigating property in the event of a release and ignition event.

[3] If other materials in the vicinity of the refrigerant are ignited, the properties of the refrigerant then no longer control the propagation of the fire.

Table 2.1 Flammability Characteristics of Refrigerants of Interest

	Lower Flammability Limit (LFL)		Upper Flammability Limit (UFL)		Minimum Ignition Energy (MIE) (mJ)		Burning Velocity (BV) (cm/s)		Density (kg/m3)	
Refrigerant	Value	Source	Value	Source	Value	Source	Value	Source	Value	Source
R-454A	8%	[2]	15%	[2]	300-1,000	[2]	2.4	[1]	3.34 (21°C)	[2]
R-454C	7.7%	[2]	15%	[2]	300-1,000	[2]	1.6	[3]	3.78 (21°C)	[2]
R-455A	11.8%	[4]	12.9%	[4]	317-331	[4]	< 1.5	[4]	3.6 (NTP)	Calc
R-516A	5.0%	[5]	14%	[6]	81	[7]	4.75	[5]	4.3 (NTP)	Calc
R-1234yf	6.2%	[2]	12.3%	[2]	5,000-10,000	[2]	1.5	[5]	4.77 (21°C)	[2]
R-290	2.1%	[2]	10.1%	[2]	0.25	[2]	46	[5]	1.83 (21°C)	[2]

Sources:
[1] Chemours Opteon XL40 Product Information Sheet, 2016
[2] FETA, 2019
[3] Chemours Opteon XL20 Product Information Sheet, 2016
[4] Honeywell Solstice L40X Product Information Brochure, 2018
[5] Kondziolka and Kim, 2019
[6] Arkema, 2020a
[7] Arkema, 2020b

2.3 Consideration of Hazard Scenarios to Be Addressed

An important part of this risk assessment is identifying those scenarios in which an ignition source will co-exist (in space and time) with a flammable concentration of released refrigerant. To better understand these scenarios, one must consider the various triggering events that could cause a refrigerant to be released, the location of the release, and the specific type of person that might be present (*i.e.*, a driver, worker, repair person, or customer) at the time of the release. It must be stressed that, during normal operations, refrigerants will be contained within the refrigeration system, and thus there is no risk of flammability events associated with the refrigerants during regular use. However, if a refrigerant is released from the equipment and (1) it is not dispersed prior to accumulating to a flammable concentration, and (2) a sufficient energy source is present, then ignition could occur. Based on the available data and discussions with the AHRI PMS, a number of scenarios were developed for evaluation as summarized below. As described subsequently, the 3-compartment trailer was assessed in detail in this report, while other scenarios were evaluated qualitatively relative to the 3-compartment trailer.

Table 2.2 Scenarios Considered in the Risk Assessment

Application	Release Scenario
Refrigerated Truck	Large leak (*i.e.*, rupture) Medium leak Small leak (*i.e.*, corrosion-induced) Releases during unit servicing
Refrigerated Shipping Container	Large leak (*i.e.*, rupture) Medium leak Small leak (*i.e.*, corrosion-induced) Releases during unit servicing
Refrigerated Single Compartment Trailer	Large leak (*i.e.*, rupture) Medium leak Small leak (*i.e.*, corrosion-induced) Releases during unit servicing
Refrigerated 3-compartment Trailer	Large leak (*i.e.*, rupture) Medium leak Small leak (*i.e.*, corrosion-induced) Releases during unit servicing

Note that a release event by itself is not sufficient to produce ignition of a refrigerant. The release 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 modeling, as described in Section 2.4, to address the question of whether flammable concentrations can be produced from refrigerant releases in transport applications.

2.4 CFD Modeling

The dispersion of a refrigerant leak in an enclosed space varies depending upon the characteristics of the space where the leak occurs – namely, the dimensions of the space, the degree of air exchange, the presence of objects (walls, obstructions, other objects) – and the conditions of the release, such as the mass release rate and chemical properties of the refrigerant. The effect of these factors on the dispersion of a leaked gas can be determined *via* CFD modeling. To support the risk assessment, we conducted CFD modeling to determine whether leaked refrigerants would attain flammable concentrations in the scenarios of interest. The CFD modeling was conducted using OpenFOAM, an open-source suite of CFD modeling packages. OpenFOAM is a widely used and validated code applicable for evaluating gas dispersion (see., *e.g.*, Mack and Spruijt, 2013). Like other CFD modeling programs, OpenFOAM divides the airspace within the simulation environment into many small cells and uses the properties of the material in question and various environmental boundary conditions (air flows, temperatures, surface interactions) to quantify the transfer of gas between adjacent cells over time.

The similarity of the scenarios evaluated in this risk assessment to prior studies informed the CFD modeling scenario selection. In prior risk assessments evaluating scenarios with similar configurations, some of the CFD modeling was found to be redundant, because flammable concentrations were not reached even under the most conservative assumptions. For example, if flammable concentrations were not formed with a large leak and were limited by the rate at which the refrigerant was being added to the system, flammable concentrations would not be expected to form at smaller leak sizes.

CFD modeling was conducted first for one compartment of a 3-compartment trailer with 25% of the volume in the compartment filled, which represented the largest free air volume among the potential simulations under consideration because other simulations considered had higher loading percentages (75%).

Impermeable shapes representing the internal refrigerated load or other objects were added to the simulation space to create the appropriate air volume. Air flow was passive (*i.e.*, the refrigeration system was off) and driven by the air currents generated by the refrigerant release. This approach is conservative for evaluating flammable concentrations, because ambient air flow will tend to disperse the refrigerant, preventing the build-up of high concentrations and contributing to refrigerant velocities in excess of the burning velocity. The model geometry used to represent the 25%-loaded 3-compartment trailer is shown in Figure 2.1.

Modeling was conducted for R-516A as the refrigerant, with an initial charge size of 18 lbs (8.2 kg). The refrigerant leak rate into the trailer space (large leak, *i.e.*, rupture in Table 2.2) was assigned to be 16 g/s, consistent with the average mass leak rate presented in ISO 20854 Annex D for accidental, rupture-type leaks. A leak orifice diameter of 3.2 mm was assumed, consistent with the leak orifice diameters used in prior evaluations of refrigerant leaks by AHRI (*e.g.*, Gradient, 2015). An initial internal pressure of 1.14 bar was assumed following discussions with the AHRI PMS. The momentum with which the refrigerant entered the space was calculated assuming orifice flow with an orifice coefficient of 0.61. Based on the mass release rate and initial charge size, the refrigerant release was calculated to last for approximately 5 minutes.

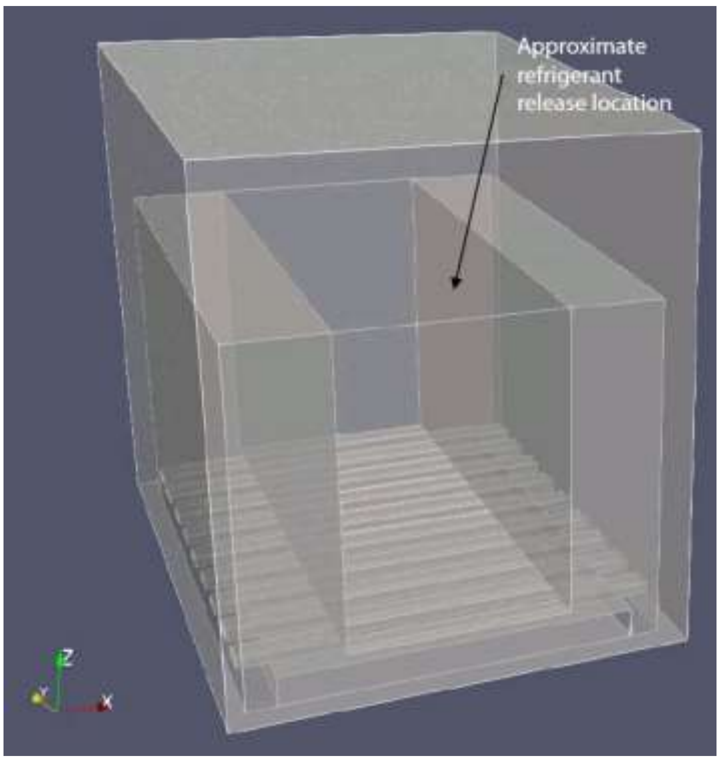

Figure 2.1 Schematic of 3-compartment trailer with 25% loading Setting Used for Simulations

The CFD modeling outputs were visualized as a video showing refrigerant release and dispersion over time, with color coding to indicate refrigerant concentrations by volume in the space. The characteristics of the release (*e.g.*, duration) were physically governed by the charge size and release rate. A screenshot from the video simulation is presented in Figure 2.2.

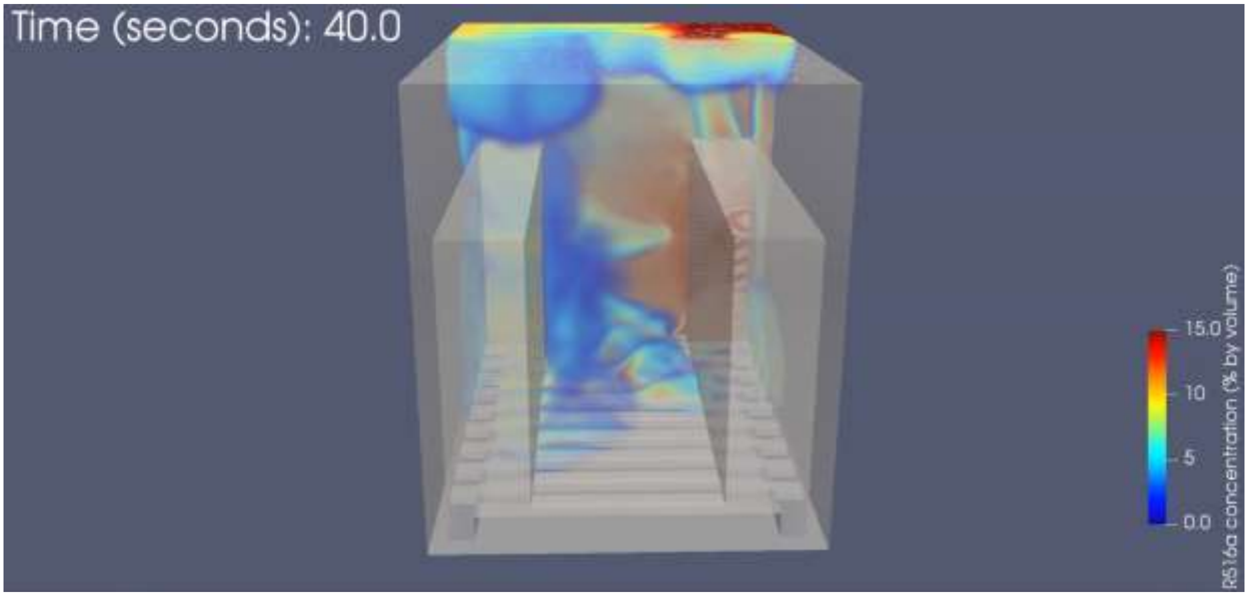

Figure 2.2 Screen Capture from CFD Simulation Video of an R-516A Release in the 3-compartment Trailer Scenario

Results for the large/rupture-type release of R-516A into the 25%-loaded 3-compartment trailer showed that concentrations of R-516A exceeded the LFL in the vicinity of the leak immediately after the leak first began, and then gradually spread throughout the trailer compartment. The refrigerant permeated along the bottom, top, and sidewalls of the trailer compartment, with the continued addition of mass leading to increasing concentrations throughout the space until the LFL was exceeded over effectively the entire trailer area. Exploratory modeling conducted with an approximately 600 cubic feet per minute (cfm) fan located over the point of the release did not prevent the formation of flammable concentrations, although it did reduce the total mass of refrigerant present in the 3-compartment trailer through time, which could reduce the severity of an ignition event, and would reduce the total time over which the LFL is exceeded.

Upon review of the 3-compartment trailer results, it was determined that modeling for other scenarios (*e.g.*, 75%-loaded 3-compartment trailers) was not necessary because the LFL had been exceeded over the entire trailer volume in the first simulation, and subsequent simulations would have similar or less free air space, so would also likely have LFL exceedances over large volumes. Unlike some of the prior stationary sector risk assessments (*e.g.*, releases into larger spaces such as a basement, attic or utility closet with louvered door), the tight sealing of the transport compartment prevents the decrease of the high refrigerant concentrations over time, leading to a long period of time above the LFL. This would be most similar to the previously modeled walk-in cooler situation where concentrations may remain high until the unit door is opened.

2.5 Data Validation

The CFD simulation geometry used in this report is similar in nature to those that have previously been validated using experimental data (Gradient, 2015). Specifically, physical experiments were conducted for small boxes with varying degrees of internal volume occupied (*e.g.*, a reach-in cooler, walk-in cooler, and small house geometry and release setup) (Gradient, 2015; Gradient, 2012). In each of the comparison experiments, the relative standard deviation for the maximum and 5-minute time-weighted average concentrations at all monitoring points except one was less than 25%, and at the majority of locations was less than 10% (Gradient, 2015; Gradient, 2012). The physical experiments validated the use of CFD as a tool to accurately determine refrigerant concentrations in the described settings. The similarity of the modeling conducted in this study to prior work (similar dimensions for the geometries) makes extension of the physical experiment validation to the conditions evaluated in this study straightforward, and the CFD results presented in this section are believed to accurately reflect concentrations that would be present were refrigerants released under the modeled conditions.

3 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 in which 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 in which 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.[4] 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 Inc., 2015).

3.1 Fault Tree Development

Appendix C contains the FT diagram developed to assess the potential ignition risks of each refrigerant for the 3-compartment trailer scenario, which was identified as the scenario most likely to pose the highest risk based on the smaller volume available for refrigerant dispersion (*e.g.*, relative to a single-compartment trailer) and higher frequency for service center visits (*e.g.*, compared to shipping containers). The FT was developed based on:

- service center site visits and interviews with industry professionals,
- publicly available analyses that were previously conducted for residential heat pump systems (Gradient, 2012) and for reach-in coolers, walk-in coolers, and remote condensing units (Gradient, 2015),
- prior risk assessments conducted for mobile air conditioning applications (Gradient, 2012; Gradient, 2013; Gradient, 2019),
- information gathered during the literature review, and
- professional judgement and discussions with the AHRI PMS.

One FT structure was developed as representative of all of the refrigerants of interest. The FT diagram in Appendix C shows the results for R-516A without a safety shut-off valve (SSOV) system installed, while results for other refrigerants and conditions are discussed in Sections 3.3 and 3.4. An SSOV typically has a spring action which closes a valve in response to detection of an electrical current failure. When there is a loss of current, the valve is de-energized and gas can no longer flow through the system. SSOVs are

[4] 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.

commonly used in gas furnaces and other appliances. SSOVs have been considered as potential mitigating measures to be installed in transport refrigeration systems employing flammable refrigerants.

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 adequate ignition source is present to ignite the refrigerant. Three types of leaks were assessed: a small leak due to corrosion or fatigue of small tubing (larger than a fugitive leak), a large leak resulting from a larger puncture or damage, and an accidental rupture-type leak. The smaller leaks are more frequent but may be less likely to release refrigerant at a large enough rate to produce flammable concentrations. The ignition sources were drawn from the comprehensive list of ignition sources in residential and commercial settings compiled by Navigant (2012) as well as from discussions with industry experts. Both electronic and flame sources were considered, as appropriate. Electronic sources include sparks from wiring shorts, faulty appliances, or similar. Flame sources include butane lighters or matches used to light tobacco products. Standards and requirements for mitigation measures for transport refrigeration applications are still in development within the industry, and there is uncertainty as to what measures will be adopted in the future. Some mitigation measures, *e.g.*, warning signals and automatic shutoffs, were included in the fault trees, but there is uncertainty in, *e.g.*, the number of detection sensors that may be present. The uncertainty was evaluated in a sensitivity analysis (Section 3.6).

Risks due to releases that could occur during recharge, repair, and servicing were also assessed. Servicing includes two basic conditions in which a refrigerant release could occur: (1) if a refrigerant was leaking prior to being brought in for servicing; and (2) if a service person intentionally or unintentionally vents the refrigerant as part of servicing. Ignition during servicing could potentially occur from spark/electronic sources, power tools, hot work performed as part of servicing, and/or from the use of lighters/matches.

3.2 Fault Tree Input Probabilities

Once the structure of the FTs was established, several sources were used to obtain the probabilities assigned to each FT input event. Many values were drawn from Gradient (2015), which included information from original equipment manufacturers (OEMs), literature sources (Colbourne and Suen, 2004; Unilever Foods, 2008; Gradient, 2009, Blackman *et al*., 2008), and established database sources (Quanterion Solutions, Inc., 2014). Probabilities concerned with the potential for flammable refrigerant concentrations in various locations were assigned based on the results of the CFD modeling, which showed a high likelihood of achieving flammable concentrations within a refrigerated compartment (Section 2.4). Table C.1 in Appendix C describes all of the probabilities used in the FTA, along with their associated rationales.

As an example of FT parameterization, consider the FT branch related to an ignition due to an R-516A release from a large leak inside a mobile 3-compartment trailer (Gate 691 on page 3 in the FT diagram in Appendix C). The probability of ignition is the product of the probability that a large leak occurs (Event 1527), the probability that there is no mitigation (Gate 698), and the probability that it ignites (Gate 696). The probability that a large leak occurs (Event 1527) was based on the reported leak frequencies in Annex D of ISO 20854. The probability that there is no mitigation (Gate 698) was calculated as the inverse[5] of the product of three events:

1. The probability that a safety shut-off valve (SSOV) is installed (Event 1531), which was an assumption made to evaluate the impact of SSOV systems (the fault tree was run both assuming presence and absence), described further in Table C.1;

[5] Gate 984 is a "NOT AND" gate, which calculates 1 minus the product of the inputs.

2. The probability that the leak sensor does not fail (Event 1532), which was based on the failure rates for gas detectors reported in the Nonelectric Parts Reliability Database (NPRD), described further in Table C.1; and
3. The probability that the SSOV does not fail (Event 1533), which was based on the failure rates for shutoff valves reported in the NPRD, described further in Table C.1.

The probability that ignition occurs (Gate 696) was the sum of the probability of ignition for each of the potential sources considered for this scenario, which included ignition by a damaged wire (Gate 695) and by sparks (Gate 822). Ignition due to a spark (Gate 822) was calculated as the product of four contributing values:

1. The probability that a spark of sufficient energy occurs (Gate 823/Event 1326), which was based on the frequency of wire shorts reported by the US NRC, the energy of sparks (ACC, 2007), and the MIE of R-516A, described further in Table C.1;
2. The probability that a flammable refrigerant cloud coincides spatially (Event 1305) and temporally (1306) with a spark source that may be present, which was based on analytical calculations and CFD modeling that showed that flammable concentrations were likely to be reached and persist throughout the compartment in a 3-compartment trailer, described further in Table C.1; and
3. The probability that environmental conditions do not prevent ignition (Gate 836), which incorporated several factors:
   - the probability that an automatic fan is not present or fails (Event 1329), which was based on the failure rates for integrated circuit digital controllers reported in the Electric Parts Reliability Database (EPRD), described further in Table C.1;
   - the probability that a warning signal would not be present or heeded (Event 1330), which was based on literature for human error (*e.g.*, Blackman *et al*., 2008), described further in Table C.1;
   - the probability that an automatic ignition source shutoff is not present or fails (Event 1928), which was an assumption based on discussions with industry experts, described further in Table C.1;
   - the probability that the burning velocity of the refrigerant does not limit ignition (Event 1327), which was based on the understanding of refrigerant flow patterns informed by the CFD modeling; and
   - the probability that temperature and humidity conditions would not prevent ignition, which were based on the properties of the refrigerants.

Data sources and analyses similar to those described above were used for the inputs in all of the probabilities used in the FTA, as detailed in Table C.1 in Appendix C.

3.3 FTA Results

Table 3.1 shows the results of the FTA. The ignition risk for R-516A used in a 3-compartment trailer without an SSOV installed was calculated as 3.1×10^{-10} events per 3-compartment trailer per year. The highest risk was posed by the potential time when the 3-compartment trailer would be serviced outdoors, and the major contributor to risk was the probability of ignition of a leak by someone using a lighter or match. Notably, the risks posed by ignition due to servicing pertaining to the refrigeration system *versus* posed by servicing pertaining to other vehicle components were of comparable magnitude (differing by a factor of approximately 2). The higher risk values for these branches relative to other settings were driven by both the higher likelihood of a refrigerant release, which was based on interviews with service center personnel, and the higher likelihood of someone using a match or lighter. Risks for ignition of the 3-compartment trailer while it was parked (but not being serviced or loaded/unloaded) and while it was being loaded/unloaded were both driven by potential ignition by a feed through plug in the condenser. Risks were lowest for the 3-compartment trailer during the time it was mobile, since leaks outside the 3-compartment trailer were determined to pose a negligibly small risk, given the air velocities that would be present while the 3-compartment trailer was mobile. While the highest risks of ignition were observed for the servicing subscenario, in which an SSOV system does not have an impact, the presence of an SSOV system was found to lower the risks of ignition in other subscenarios by approximately an order of magnitude.

Table 3.1 Results of the FTA for the 3-compartment Trailer

Subscenario	Risk of R-516A Ignition in a 3-compartment trailer application (Events per Unit per Year)
SSOV Installed	
Parked (not in service or being loaded/unloaded)	1×10^{-12}
Mobile	3×10^{-16}
In servicing	3×10^{-10}
Being loaded/unloaded	8×10^{-14}
SSOV Not Installed	
Parked (not in service or being loaded/unloaded)	5×10^{-12}
Mobile	2×10^{-15}
In servicing	3×10^{-10}
Being loaded/unloaded	4×10^{-13}

Notes:
FTA = Fault Tree Analysis; R-516A =Azeotropic Blend of R-1234yf, R-134a, and R-152a; SSOV = Safety Shut-off Valve.
Risks for the small, large, and rupture leaks are combined in these results.
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 can be recognized more easily.

3.4 Other Refrigerants

The FTA developed for R-516A described in Sections 3.1-3.3 was modified to calculate risks for other refrigerants of interest. Many of the input probabilities to the FT are consistent regardless of refrigerant evaluated, *e.g.*, the frequency with which a 3-compartment trailer undergoes servicing. However, as noted above other inputs can vary by refrigerant and can lead to different risks for different refrigerants. FTA inputs related to refrigerant-specific MIE, impacts of temperature and humidity on flammability range, burning velocity, and flammable concentration range were adjusted to evaluate risks posed by refrigerants other than R-516A. Additional refrigerants R-454A, R-455A, R-1234yf, and R-290 were selected in consultation with the AHRI PMS as refrigerants that are relevant to potential uses in transport refrigeration and also cover a range of potential flammability properties. R-290, an A3 refrigerant, was included for comparative purposes with the A2L refrigerants. As discussed in Section 1, AHRTI (2019) demonstrated that the consequences of A3 refrigerant ignition are likely to be more significant than the consequences of A2L refrigerant ignition. Table C.2 in Appendix C details which parameters in the FT were adjusted to account for variations in refrigerant properties. In-particular, values related to the MIE (*e.g.*, the likelihood of a spark igniting a cloud of flammable refrigerant) were varied by several orders of magnitude to account for the wide range in MIEs among and between the A2L refrigerants the A3 refrigerant. For example, while friction sparks have been shown to be an implausible ignition source for R-1234yf (probability assigned as 0), friction sparks typically exceed the MIE of R-290 and the probability that a friction spark could ignite R-290 was set to 1 in Table C.2. Table 3.2 summarizes the results of the FTA by refrigerant. Consistent with the results for R-516A, while the highest risks of ignition were observed for the servicing subscenario for each refrigerant, in which an SSOV system does not have an impact, the presence of an SSOV system was found to lower the risks of ignition in other subscenarios by approximately an order of magnitude. As discussed in Section 3.2, the probability of the SSOV system correctly working to mitigate the release is based on the probability that both the refrigerant leak detector and the shutoff valve do not fail. While the calculated risks of ignition between the A2L refrigerants and the A3 refrigerant differ by one to three orders of magnitude (Table 3.2), the difference in consequences may be even larger based on the observations in AHRTI (2019).

Table 3.2 Risk of Ignition in a 3-compartment trailer application (Events per Unit per Year) by Refrigerant

Safety Group	A2L				A3
Subscenario	**R-516A**	**R-454A**	**R-455A**	**R-1234yf**	**R-290**
SSOV Installed (all subscenarios combined)	3×10^{-10}	3×10^{-10}	3×10^{-10}	3×10^{-10}	5×10^{-9}
Parked (not in service or being loaded/unloaded)	1×10^{-12}	5×10^{-13}	9×10^{-14}	9×10^{-13}	5×10^{-11}
Mobile	3×10^{-16}	6×10^{-17}	6×10^{-17}	6×10^{-18}	6×10^{-15}
In servicing	3×10^{-10}	3×10^{-10}	3×10^{-10}	3×10^{-10}	5×10^{-9}
Being loaded/unloaded	8×10^{-14}	5×10^{-14}	3×10^{-14}	8×10^{-14}	3×10^{-12}
SSOV Not Installed (all subscenarios combined)	3×10^{-10}	3×10^{-10}	3×10^{-10}	3×10^{-10}	5×10^{-9}
Parked (not in service or being loaded/unloaded)	5×10^{-12}	2×10^{-12}	5×10^{-13}	5×10^{-12}	2×10^{-10}
Mobile	2×10^{-15}	3×10^{-16}	3×10^{-16}	3×10^{-17}	3×10^{-14}
In servicing	3×10^{-10}	3×10^{-10}	3×10^{-10}	3×10^{-10}	5×10^{-9}
Being loaded/unloaded	4×10^{-13}	3×10^{-13}	2×10^{-13}	4×10^{-13}	2×10^{-11}

Note: As discussed in Section 1, the consequences of A3 refrigerant ignition (*e.g.*, burn energy, flame propagation, pressure generation) are likely to be significantly greater than A2L refrigerant ignition. Thus, while the calculated risks of ignition occurring differ by one to three orders of magnitude, the difference in consequences may be even larger.

3.5 Interpretation of the FTA Results

The results of an FTA are best used in a comparative sense, in relation to risks that are known and judged reasonable or unreasonable by society at large. A complete avoidance of risk is not possible; any everyday activity involves some element of risk (*e.g.*, driving a car, eating at a restaurant). 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. These comparison risks are shown in Table 3.3. As can be seen in this table, the risks due to release and ignition of any of the A2L refrigerants in the 3-compartment trailer application are below risks of other hazards that are commonly accepted by the public as being reasonable. For example, the highest risk of ignition (3×10^{-10} per unit per year) is well below the risk of a fire event for a semitrailer on the highway (2×10^{-3} per building per year). Although R-290 is more flammable than any of the A2L gases, its highest risk scenario at 5×10^{-9} is also well below this comparative value. As discussed in Section 1, however, AHRTI (2019) demonstrated that the consequences of A3 refrigerant ignition are likely to be more significant than the consequences of A2L refrigerant ignition, and while the calculated risks of ignition between the A2L refrigerants and the A3 refrigerant differ by one to three orders of magnitude (Table 3.2), the difference in consequences may be even larger. Thus, the acceptable thresholds for the risk of ignition may be different for A2L refrigerants *vs*. A3 refrigerants. Note that the FTA evaluated refrigerant ignition and did not determine whether the ignition resulted in a fire affecting other structures, or consequences of ignition, or the severity of ignition. Not all ignition events are likely to initiate fires (Tewarson *et al*., 2000; Southwest Research Institute, 2005; Walters *et al*., 2000), and comparison of ignition risks to fire statistics is therefore conservative. While the results in Table 3.2 show that inclusion of the SSOV as a potential mitigation measure does not impact on the service scenario, which is the risk driver, SSOV systems do result in approximately an order of magnitude reduction of ignition risk in the other scenarios, which may be important because these scenarios involve risks to individuals with less training related to flammable refrigerants. As discussed in Section 3.2, the probability of the SSOV system correctly working to mitigate the release is based on the probability that both the refrigerant leak detector and the shutoff valve do not fail.

Table 3.3 Comparison of FTA-derived Risks to the Risks of Other Relevant Hazards

Relevant Hazard	Risk per Unit per Year	Source
Commercial building fire significant enough to warrant fire department response	2×10^{-2}	NFDC (2013)
Fire on a marine transport ship (per ship per year)	1.4 to 1.6×10^{-2}	IAEA, 2001
Fire originating in cargo hold of a ship (per ship per year)	5×10^{-4}	IAEA, 2001[a]
Highway fire for semitrailer with or without tractor	2×10^{-3}	NFPA, 2020; EDF 2021[b]
Fatal injury at work (all occupations)	3×10^{-5}	NSC (2016)
Injury at work due to fires or explosions	2×10^{-5}	US BLS (2016)
Commercial cooler unit refrigerant ignition (R-32)	10^{-9} to 10^{-11}	Gradient (2015)
Risk of refrigerant ignition for A3 [R-290] (3-compartment trailer)	5×10^{-9}	Current analysis[c]
Risk of refrigerant ignition for A2L (3-compartment trailer)	3×10^{-10}	Current analysis

Notes:
CDC = Centers for Disease Control and Prevention; CPSC = US Consumer Product Safety Commission; FTA = Fault Tree Analysis; NFDC = National Fire Data Center; NFPA = National Fire Protection Association; NSC = National Safety Council;
(a) Taking the average of all fires in marine transport (1.5×10^{-2}) and multiplying by 3 percent, the frequency of fires that begin in the hold.
(b) NFPA (2020) reports an average of 6,400 vehicle highway fires per year from 2013 to 2017 for the category "semitrailer with or without tractor". This is divided by 3.15 million class 7 and 8 regional and long haul trucks estimated to be in service in December 2020 (EDF, 2021). This results in a frequency of 2×10^{-3} per year.
(c) As discussed in Section 1, the consequences of A3 refrigerant ignition (*e.g.*, burn energy, flame propagation, pressure generation) are likely to be significantly greater than A2L refrigerant ignition. Thus, while the calculated risks of ignition occurring differ by one to three orders of magnitude, the difference in consequences may be even larger.

3.6 Data Gaps and Sensitivity Analysis

This risk assessment was geared towards addressing a specific set of questions concerning the use of specific refrigerants (R-516A, R-454A, R-455A, R-1234yf, R-290) in transport refrigeration applications. 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 leak rates, operator behavior, mitigation requirements, and repair practices.

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 C) 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 that 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.

We chose to vary combinations of uncertain inputs rather than individual inputs in isolation to better characterize the magnitude of effects on the FTA results. We focused on the risk-driving branch of the FTA, which was the servicing scenario. Three different combinations of inputs were varied to test the sensitivity of the results to different potential uncertainties:

- Increase the amount of time the 3-compartment trailer spends in a servicing environment.
- Increase the frequency with which a refrigerant is released during servicing due to incomplete discharge.
- Increase the potential for ignition sources to coincide with flammable concentrations.

The parameters modified as well as the results of the analysis are shown in Table 3.4.

While the modifications shown in Table 3.4 produced a change in the estimated risks, none of the changes were substantial enough to alter the conclusions of the risk assessment (*i.e.*, ignition risks were still far below the risks of the comparison events shown in Table 3.3). It should also be stressed that the risk estimates in Table 3.4 were the result of changing base-case inputs that are considered reasonable. They could possibly represent conditions for specific installed units, but do not reflect the average risk across the entire 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 3.4 Sensitivity Analysis Results

Input Modification	Value Change	Modified Risk of R-516A Ignition, SSOV Not Installed (Events per Unit per Year)	Comment	Modified Risk of R-290 Ignition, SSOV Not Installed (Events per Unit per Year)	Comment
Increase fraction of time a 3-compartment trailer spends in servicing	Event 1077: 0.003 to 0.01 Event 1075: 0.81 to 0.71	1×10^{-9}	Approximately 1 order of magnitude increase in risk, but still well below comparison risks from other events	2×10^{-8}	Approximately 1 order of magnitude increase in risk, but still well below comparison risks from other events
Increase the frequency with which refrigerant is released during servicing due to incomplete discharge	Event 1336: 0.25 to 0.5	4×10^{-10}	Slight increase in overall risk, but comparable to base case	6×10^{-9}	Slight increase in overall risk, but comparable to base case
Increase potential for ignition source coincidence with flammable concentrations	Event 1350: 1×10^{-4} to 1×10^{-3} Event 1351: 2×10^{-6} to 2×10^{-3}[a] Event 1362: 0.001 to 0.01 Event 1340: 1×10^{-4} to 1×10^{-3} Event 1341: 2×10^{-6} to 2x10-3[a] Event 1380: 0.001 to 0.01	3×10^{-9}	Approximately 1 order of magnitude increase in risk, but still well below comparison risks from other events	6×10^{-8}	Approximately 1 order of magnitude increase in risk, but still well below comparison risks from other events

Note:

R-516A =Azeotropic Blend of R-1234yf, R-134a, and R-152a.

(a) Probabilities for R-290 were adusted by the same factor where exact values differed, *e.g.*, from 6×10^{-6} to 6×10^{-3}, rather than from 2×10^{-6} to 2×10^{-3}.

4 Conclusions and Recommendations

This risk assessment was aimed at evaluating the potential risks of using new lower GWP refrigerants in the refrigerated transport sector. Although widespread use of a flammable refrigerant in this application 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-404A may require rethinking previous paradigms. If the risk of ignition and consequence of ignition associated with these new refrigerants is shown to be incrementally small compared to other tolerated risks in the industry, the environmental benefits these alternative refrigerants can provide (in terms of substantially reduced GWP) may be considered an appropriate basis for substitution. Prior risk assessments for stationary sector applications have found the use of A2L refrigerants to pose acceptably low levels of risk, and that the impacts or consequences of ignition increase between Safety Group A1, A2L, and A3 refrigerants, *i.e.*, the consequences of A3 refrigerant ignition are likely to be more significant than the consequences of A2L refrigerant ignition, and the acceptable risk tolerance for ignition of A2L refrigerants may be higher than that for A3 refrigerants. Leak detection sensors to deploy SSOV systems, which are being considered for use in transport refrigeration applications, may serve as additional mechanisms to mitigate the risks posed by the use of flammable refrigerants.

A number of potential concerns were outside the scope of this analysis. This assessment looked at the risks of refrigerant ignition and not the consequences of that ignition. Because ignition is required, but may not be sufficient to produce a fire (*i.e.*, the ignition event has to be propagated to other fuel sources), the risk of ignition is a conservative proxy for the risk of fire. Similarly, all fluorocarbon refrigerants decompose under sufficient temperature conditions to produce hydrogen fluoride (HF) and related compounds. This is true for R-404A as well as for the A2L refrigerants, although the greater flammability of A2L refrigerants increases the likelihood of ignition leading to HF generation. HF is highly reactive and exposure to HF at sufficient concentrations can produce substantial adverse health effects. HF production at significant contributions requires fluorocarbons to be combusted and thus the risk of refrigerant ignition can also serve as a proxy for HF formation from refrigerant combustion. While HF can also be produced from decomposition of fluorocarbons on hot surfaces (*i.e.*, greater than approximately 500 C), which are not sufficient to cause ignition, such hot surfaces are not expected to be present in these transport scenarios. 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. Other consequences of ignition, such as overpressure of compartments, could also be examined particularly in the case of A3 refrigerants such as R-290. Prior risk assessments for stationary sector applications have found that the severity and consequences of ignition increase between Safety Group A1, A2L, and A3 refrigerants, *i.e.*, the consequences of A3 refrigerant ignition are likely to be more significant than the consequences of A2L refrigerant ignition.

During normal operation, refrigerant gas 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 these gases can be released with the possibility of ignition. Risks based on typical system design and installation, estimated at 5×10^{-9} to 3×10^{-10} events per unit per year (for R-290 and the A2Ls, respectively), are well below the existing risk of highway fires that occur with truck transportation due to other causes (estimated at 2×10^{-3} per vehicle 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.

Safety shut-off valve systems (SSOV systems) were found to reduce risks among all operational conditions except for servicing, where an SSOV would not be in operation, by approximately an order of magnitude. For the servicing scenario, the risk assessment did not identify significant differences between transport refrigeration applications having a safety shut-off valve (SSOV) to stop the leakage of refrigerant into the space because leaks in the servicing scenario were based on observational data on the number of leaks that are brought in for servicing under current conditions. It is plausible that an SSOV system would reduce the number of units brought in with active leaks, but this assessment does not estimate the potential magnitude of that reduction. An SSOV did reduce risks for other scenarios, *e.g.*, while a 3-compartment trailer is parked but not in servicing. Further, CFD modeling showed that including a fan above the evaporator to ventilate the refrigerated space did not prevent the formation of flammable concentrations.

In summary, this risk assessment evaluated the potential ignition risks associated with the use of lower GWP refrigerants in refrigerated transport. Based on CFD modeling and FTA, the risk assessment indicates that the overall average risks associated with the use of these gases 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. The risks of the A2L refrigerants were shown to be lower than the risks of the A3 refrigerant.

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Appendix A

Literature Review Summary Table

AHRI Refrigerated Transport Literature Review Summary, December 2020

Author	Date	Title	Publication type	Comment
US DOT	2020	Large Truck and Bus Crash Facts 2018	Report	Apparently the most recent of a series of annual reports on large truck and bus crashes. Provides information on collision frequencies for large trucks and passenger vehicles. Data are broken down by severity of crash (property damage only, injury, fatality). Some information on factors causing a crash. No breakdown by truck type involved.
Ryder, Jordan and Sunderland (NFPA)	2019	Flammable refrigerants fire fighter training: Hazard assessment and demonstrative testing	Report	Provides general information on refrigerant systems. Does not mention refrigerated transport, focuses only on stationary and automotive applications.
Vestergaard, N. Danfoss Industrial Refrigeration	2019	Safety in ammonia systems	Slide presentation	Provides some information on transport accidents but these appear to be related to bulk ammonia transport. Some discussion of risks for stationary systems.
Zloczowska, E	2018	Maritime containers refrigeration plan faults survey		Provides some useful information on refrigerant leakage in shipping containers. Provides no leak frequency data but does give data on the percentage of system faults for refrigerated containers that involve refrigerant leaks, power system faults, mechanical component faults, etc. "On average, 3% of transported refrigerated containers have failed during a single voyage."
CEN/TC 182	2018	Status report from technical committee regarding new standards under development	Standard	Discusses an ISO standard for refrigeration systems which includes transport refrigeration. Currently available as ISO 20854:2019-10. Standard covers safety requirements for the design of container refrigerating systems; design and construction of the refrigerating systems; design-related requirements of the mechanical refrigeration unit (MRU) manufacturer for safe service, maintenance, and repair; general recommendations at operating sites; safe operation at different operating sites; and servicing recommendations and requirements at operating sites
Snapp, S.	2017	How best to understand your refrigerated transport options	Webpage	Provides basic information on refrigerated transport systems. No useful details to support FTA.
Manadiaar, H.	2017	The essential guide to cargo damage		Focuses on loss of shipping container contents, no useful information regarding refrigeration systems.

Author	Date	Title	Publication type	Comment
Francis et al.	2017	An investigation of refrigerant leakage in commercial refrigeration	Journal article	Reviewed abstract only. Focuses on supermarket systems. "Over 82% of the recorded leaks were from R404A systems, and mainly consisted of pipe or joint failures or a leaking seal/gland/core located in the compressor pack and the high pressure liquid line."
Colbourne et al.	2017	Development of R290 transport refrigeration system	Conference paper (Institute of Refrigeration [IOR], 2017)	Provides some information on possible sources of ignition for transport systems. Reports on some leak simulation tests in systems and the concentration of refrigerant near the ignition source. Refers to leak frequencies from a prior study of R290 systems (Jansen and van Gerwen, 1995), reports some of the leak frequencies (e.g., condensing unit, evaporator unit, refrigerated space). States the background fire risk (that is not due to flammable refrigerants) is about 2E-5 per year for AC units and 1E-5 per year for domestic refrigerators in the UK. Determines the risk of R290 in transport systems is "easily considered as negligible".
Peterman, DR. Congressional Research Service	2017	Commercial truck safety: overview	Report	Some qualitative information about truck road crashes. A limited amount of data from DOT databases. No specific information on refrigerated vehicles.
US DOT	2017	Commercial motor vehicle – Traffic Safety Facts	Handout	All information is about fatal crashes and thus not helpful for parameterizing FTA (where concern would be about all crashes or at least those severe enough to cause a leak).
Guchen Thermo	2017	How to check whether refrigerant in truck refrigeration unit is leaking	Webpage	Provides some information on methods for checking leaks. No other useful information.

Author	Date	Title	Publication type	Comment
United Nations Environment Programme Technology and Economic Assessment Panel	2017	Decision XXVIII/4 Task Force Report Safety Standards for Flammable Low Global-Warming-Potential (GWP) Refrigerants	Report	Section 4.3 discusses many of the elements important for assessing risk. However, the document generally provides an overview of what has been done and does not give specifics. Notable is the following statement: "Possibly the most important is the frequency of leaks, and particularly, the frequency of leaks of a given hole size. *Empirical data for this is extremely scarce* so approximations and assumptions are normally used. Other information is the location of leaks (and the probability of their occurrence) and the mechanism for the leak development (e.g., corrosion, mechanical impact, etc.) so that the rate of hole development can be considered." (p. 28) it does provide a number of potentially useful references (included in this table).
US DOT, Federal Transit Administration	2016	Rail safety statistics report 2007-2013	Report	Exclusively focused on passenger rail, not helpful for this project.
Poolman C., Papas P., Rusignuolo G. et al.	2016	Low GWP refrigerants in transport refrigeration: risk and benefit assessment of flammable and mildly flammable alternatives.	Conference paper	A risk assessment of transport applications. Refrigerants addressed include R-32, R-1234yf, R-1234ze(E) and R-290. Three conditions evaluated: system operating, system off, system off and unplugged from auxiliary power. Refers to work by Papas et al. (2016) re: flammability testing of A2Ls in shipping containers. Refrigerant dispersion assumed uniform mixing. Figure 2 presents risk results but this is apparently only the risk of having a certain percentage of the LFL, not that the refrigerant ignites. The authors note that assessing the probability of leak and ignition events is outside of the scope of the paper. Also discusses possible mitigation measures.
UNEP	2015	Lower GWP alternatives in commercial and transport refrigeration: An expanded compilation of propane, CO2, ammonia and HFO case studies	Report	Good qualitative discussion of technologies. Case studies presented. Provides very little information about safety or risks, no information about leaks.
EU	2014	EU F gas regulation sheet. Information sheet 4: Transport refrigeration	Information sheet	Other than a discussion of mandatory leak checks (possibly useful for fault tree parameterization), provides no useful information

Author	Date	Title	Publication type	Comment
Goetzler et al.	2014	Research & development roadmap for next generation low global warming potential refrigerants	Report	Focusses on stationary sector applications, no discussion of transport. More of an overview paper with little in the way of testing results.
US EPA	2011	Transitioning to low-GWP alternatives in transport refrigeration	Webpage	Provides some general information but is lacking in detail
Schwartz, W; Hamisch, J.	2003	Final report on establishing leakage rates of mobile air conditioners	Report	Focuses on fugitive emissions from mobile AC systems, mostly slow leaks over time. Of minimal importance to the current project.
Toth et al. [NHTSA]	2003	Large truck crash causation study in the united states.	White paper	Describes NHTSA efforts to create a database from the on-going Large Truck Crash Causation Study. Provides a few results but the database is still under construction according to the document. Refrigerated vans were involved in 14 of 166 total crashes in the preliminary dataset (final dataset should reach 1000 crashes). Some frequency information about vehicle failure causes (operator error, equipment malfunction).
Hansen et al.	2002	Occupational accidents aboard merchant ships	Journal article	Focuses on worker accidents only, no information on failures of ship components that might affect refrigeration.
International Atomic Energy Agency	2001	Severity, probability and risk of accidents during maritime transport of radioactive material	Report	Provides some data on the frequency of fires, explosions and collisions of maritime vessels. Provides some information on the origin of fires on a ship. No specific information on refrigerated containers.

Author	Date	Title	Publication type	Comment
Jansen and van Gerwen. [TNO]	1995	Risk assessment of the use of flammable refrigerants	White paper/report	Describes a quantitative risk assessment involving two transportation systems (small [3kg] and large [8 kg]) and three refrigerants - butane, propane and LPG . Considered normal operations, maintenance and repair, and transport (road accidents). Uses simple dispersion modeling (Gaussian dispersion model). Seems to assume that if a release occurs there will be ignition. Maximum risk is in the range of 10^{-6} per unit per year (Figures 4 and 5) Determined the risk for such systems is acceptable. Did not consider mitigation or other factors. Reports on the results of a literature survey but this only includes a stationary scenario risk assessment and several standards. Provides a description of truck transportation systems including some physical parameters of these systems (e.g., diameter and length of lines, volumes). Provides release frequencies probabilities from different components (per unit per year). Gives accident frequency data. Risk calculations seemingly fairly simple and not explained well; refers to other documents which are not readily available.
Gerwen, R. J. M., van, Jansen, C. M. A.	1994	Risk assessment of flammable refrigerants.	Conference paper	Unavailable but seems to be an early presentation of the TNO 1995 report.
Burnette and Baker	Undated	A study of R134a leaks in heavy duty vehicles (presentation)	Slide presentation	Focuses on fugitive emissions from vehicle AC systems (e.g., buses). Not helpful for the current project.
Begam. Marks and Traulsen	Undated	2015-2017 An analysis of fatal truck accident statistics	Webpage	Limited information. Attorney website, US DOT data would be a better source.
UK P&I	Undated	Top 25 causes of container claims	Webpage	General reference, not particularly helpful, no detailed information.

Author	Date	Title	Publication type	Comment
European FluoroCarbons Technical Committee (EFCTC)	Undated	Transport refrigeration 2019	Webpage	Povides no useful information for the current project.
Kantharia, R	Undated	8 most common problems found in ship's refrigeration system	Webpage	Gives some useful information on failure mechanisms for container ship systems. Focuses on a ship-wide refrigeration system rather than individual refrigerated container units.
Diesel News	Undated	The common causes of fires in trucks and trailers	Webpage	Provides some qualitative information of causes of fires in trucks. Gives no quantitative data but potentially useful for fault tree scenario development.
United Worldwide Transportation	Undated	8 common malfunctions: refrigerated truck delivery service providers face and what to do to prevent them	Webpage	Provides some qualitative information on causes of leaks in reefer containers, No quantitative data but potentially useful for fault tree scenario development.

Appendix B

Facility Visit Survey and Notes

Gradient Proposed Questions for Service Center Professionals*

We are working with the Air Conditioning, Heating, and Refrigeration Institute (AHRI) to understand potential risks if mildly flammable (ASHRAE Class 2L) refrigerants are adopted for use in refrigerated transport systems at some time in the future. These refrigerants have already been successfully adopted for use in automotive AC systems but many aspects of refrigerated transport are different. The goal is to understand potential health risks so that procedures can be implemented should these materials be put into use. As input to our analysis, we need data on a number of issues covered in the questions below. This kind of information does not appear to be readily available so we need the help and expertise of service center personnel to understand some of these issues.

*The questions may be adapted *ad hoc* to follow-up on provided responses.

1. How many (**refrigerated shipping containers/refrigerated trucks/refrigerated trailers of varying compartment numbers**) have you worked on at this job? What percent of each type do you typically service in a month?
2. Do you have a sense of what percentage of the (**refrigerated shipping containers/refrigerated trucks/refrigerated trailers**) in circulation each year require servicing?
    a. Out of warranty? / In warranty? / Both?
3. Do you see any of the following types of problems in products to be serviced and how frequently (as a % of service jobs)?

Refrigerated trucks

Type of Problem	**How frequently (% of service jobs)**
Small refrigerant leak	
Wiring problems Low Voltage <48V	
Wiring problems High Voltage >48V	
Tube/hose breakage	
Evaporator coil failure	
Condenser coil failure	
Other (please describe) examples: 3rd party modifications, unusual or unexpected events, *etc.*	

Refrigerated trailers

Type of Problem	**How frequently (% of service jobs)**
Small refrigerant leak	
Wiring problems Low Voltage <48V	
Wiring problems High Voltage >48V	
Tube/hose breakage	
Host Evaporator coil failure	
Condenser coil failure	
Remote evaporator coil failure	
Other (please describe) examples: 3rd party modifications, unusual or unexpected events, *etc.*	

Refrigerated shipping containers

Type of Problem	How frequently (% of service jobs)
Small refrigerant leak	
Wiring problems Low Voltage <48V	
Wiring problems High Voltage >48V	
Tube/hose breakage	
Host Evaporator coil failure	
Condenser coil failure	
Other (please describe) examples: 3rd party modifications, unusual or unexpected events, *etc.*	

4. What are the most common causes of repair jobs you've seen?

Refrigerated trucks

Type of Problem	How frequently (% of service jobs)
Normal wear and tear/aging	
Improper repair	
Road damage (*e.g.*, stone hits)	
Intentional (vandalism)	
Other (please describe)	

Refrigerated trailers

Type of Problem	How frequently (% of service jobs)
Normal wear and tear/aging	
Improper repair	
Road damage (*e.g.*, stone hits)	
Intentional (vandalism)	
Other (please describe)	

Refrigerated shipping containers

Type of Problem	How frequently (% of service jobs)
Normal wear and tear/aging	
Improper repair	
Road damage (*e.g.*, stone hits)	
Intentional (vandalism)	
Other (please describe)	

5. Are service pits used at this facility?
6. Is there an HVAC system at the service facility? Is it always running, or if not, when does it run? Is there any other ventilation beyond general facility HVAC?
7. Is equipment requiring servicing all brought to the service center, or what percent of the servicing work is performed in the field? What percent is done indoors *vs*. outdoors?

8. What percentage of time are products serviced when they still have a full refrigerant charge? What percentage have a partial charge (*i.e*., they are actively leaking)? What percentage have no charge left? When the charge is not full, how has the refrigerant escaped? What are typical leak locations (*e.g*., bottom of the condenser, loose hose)? When repairs are done, do you always completely evacuate the charge beforehand? If so, to what level of vacuum?
9. Are there protective requirements in place in case any electrical components are still live, and/or potentially producing sparks?
10. What percentage of time is servicing needed as a result of a vehicle or cargo vessel crash, rather than an equipment or some other failure?
11. Can you describe 2 or 3 cases that indicate the most damaged equipment you've seen? We're trying to get a sense of the worst-case damage situation.
12. For refrigerated trucks, do you ever do work on the cabin AC components, or just the refrigerated transport parts?
13. What types of safety protocols are in place at this service center? If there is a safety issue (fire, *etc*.), what does evacuation look like? Are drills ever performed? What are the safety protocols if service personnel encounter a fire situation in the field?
14. What types of equipment are used to service products? How often are flame/torch leak detector devices used? How often is welding/brazing performed? How often is hot work performed, and where? How often are power tools used, and for what percentage of the day when used?
15. Have there ever been any fire issues at this service center, or when servicing equipment in the field?
16. Have you ever experienced exposure to hydrogen fluoride (HF), an irritating gas that can be produced when some refrigerants are exposed to hot sources? If yes, tell us about that.
17. Can you describe any safety incidents related to the refrigeration system that may have occurred at this service center or when servicing equipment in the field?
18. What are the rules regarding smoking at this service center? Is it your experience that people generally follow those? Do you know roughly how many people working at the facility smoke? How many employees are there total (*e.g*., 10, 50, 100)? How many carry lighters?
19. How frequently are non-employees at the service center? What are the general hours of operation, and how long does an individual employee spend working?
20. Does everyone carry cell phones with them in the work area?
21. How frequently are refrigerant containers recharged (*i.e*., what fraction of service calls require recharging)? What recharging methods are used? Are containers always checked for leaks before being recharged? Are leaks in containers ever missed, and require a second servicing effort?
22. How are refrigerants transferred and/or disposed? Is there ever any venting to the atmosphere?
23. What possible repair-related refrigerant ignition scenarios can you envision, both at this facility and in the field, and at 3rd parties?
24. What type of education regarding flammable refrigerants do technicians need to go through (or would you expect will be required in the future)?
25. What is your assessment of how often repairs are done by 3rd parties on either;
    a. Refrigeration system
    b. Body repairs / modifications. Any insights in the prevalence of welding by 3rd parties.

26. What experiences can you share about damage scenarios from loading/unloading (e.g. forklift damage to host evaporator or remote evaporators. Both unit running and non-running conditions.

<u>For refrigerated trucks only</u>

27. In the event of a collision, how likely is it that the radiator is also damaged, releasing steam?
28. Are all of the products you work on diesel motor based?

Other

29. Any other comments or insights that you can share that can help further understanding of refrigerant loss and heat or spark sources?

Thanks for your assistance, it will help us to produce a much stronger analysis!

Memorandum

To: File **Date:** December 14, 2020

From: John Kondziolka and Tom Lewandowski, Gradient

Subject: Refrigerated Transportation Service Center Visits

Gradient, working on behalf of the Air Conditioning, Heating, and Refrigeration Institute (AHRI), visited two refrigerated transportation service centers as part of a project to understand the potential risks of lower flammability (American Society of Heating, Refrigerating, and Air-conditioning Engineers [ASHRAE] Class 2L) refrigerants are adopted for use in refrigerated transport systems at some time in the future.[1] The refrigerated transport systems of interest include refrigerated shipping containers, refrigerated trucks, and refrigerated trailers. A questionnaire was distributed to service center professionals in advance of the visits and is included as Attachment A. The service center visits included tours of the facilities as well as personnel interviews based on the questionnaire. Each service center visit also included interviews with representatives from a second service center. Gradient has on file the written responses to the surveys, as well as photographs taken during the site visits, but this detailed information is not included in this memorandum as it is confidential business information.

Information obtained from the site visits that can be shared while respecting confidentiality includes the following:

- The number of service invoices addressed by the service center facilities was on the order of 10,000 per year. About 20% of the work at the service center facilities is non-refrigeration-related (*i.e.*, related to other system components), while 80% is refrigeration-related. Approximately 60% of the refrigeration-related work is repair. Repair times can range from less than 2.5 hours to longer than 2 weeks, depending on the system and type of repair. Repairs are also performed in the field using mobile repair trucks (*e.g.*, for busses and public transit).
- Some repair work at the service centers is routine maintenance, for example, vehicles being brought in for service after a fixed number of hours of operation. The estimates for repair work performed under warranty ranged from less than 1% to 70%, depending on the service center.
- Auxiliary power units (APUs), while not one of the systems originally of interest, comprise a significant volume of the units addressed at some of the service centers. APUs typically have small refrigerant leaks or tube/hose breakages, unless third-party vendors work on the units, in which case large leaks are most common.
- For refrigerated trucks, most problems to be serviced are small refrigerant leaks or low-voltage wiring problems.

[1] Interviews with other facilities were planned but we were unable to schedule these and the decision was made to prepare this summary based on the information that was obtained.

- For refrigerated trailers, the most frequent issues requiring service are small or large refrigerant leaks or low-voltage wiring problems.
- For refrigerated shipping containers, small refrigerant leaks are rare, and, in general, shipping container repair is not common.
- For all units, 70%-80% of repair work performed at the service centers is due to normal wear and tear or aging. Other types of common repair include fixing improper repair by third-party vendors, road damage, and forklift damage.
- Heating, ventilation, and air conditioning (HVAC) systems were uncommon in the repair areas (but the facilities visited were not in severe climate locations). A substantial portion of the repair work occurs outdoors. 30%-50% of repair work occurs in the field, away from the service center.
- Most vehicles in for repair have low or empty refrigerant charge when they reach the service center. Most refrigerant leaks are pinhole leaks. Any remaining refrigerant charge is removed before repair. Leaks are most common in evaporator and condenser coils. The worst damage typically observed for vehicles is if the vehicle hits a bridge.
- Respondents indicated the following regarding potential ignition sources. Repairs are commonly performed near and with live electric system components. Welding/brazing is commonly performed in the vicinity of repairs. Power tools are used regularly. Hot work is less common. Flame/torch detectors are not used to check for leaks. Most repair personnel carry lighters. Intentional venting of a refrigerant to the atmosphere is never performed.

Appendix C

Fault Trees and Input Values Table

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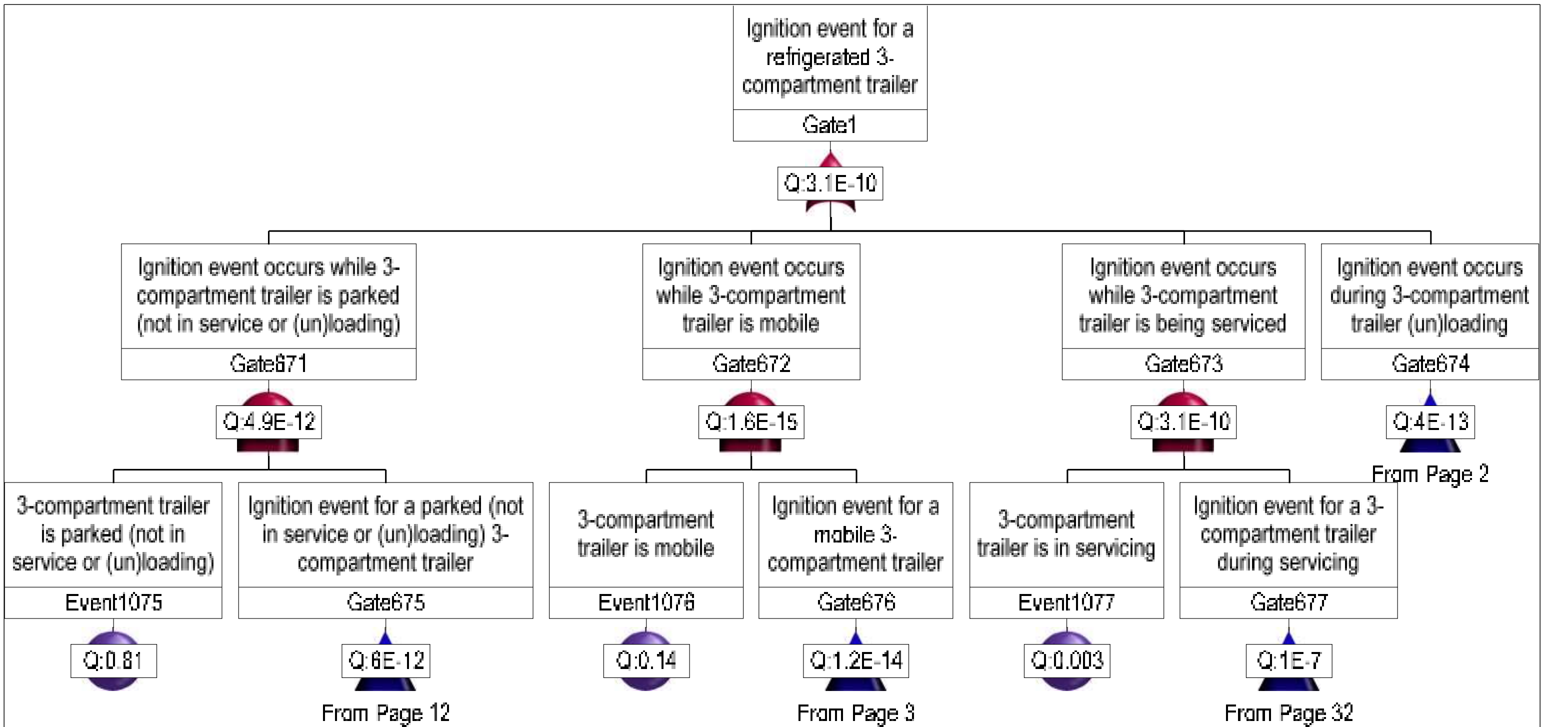

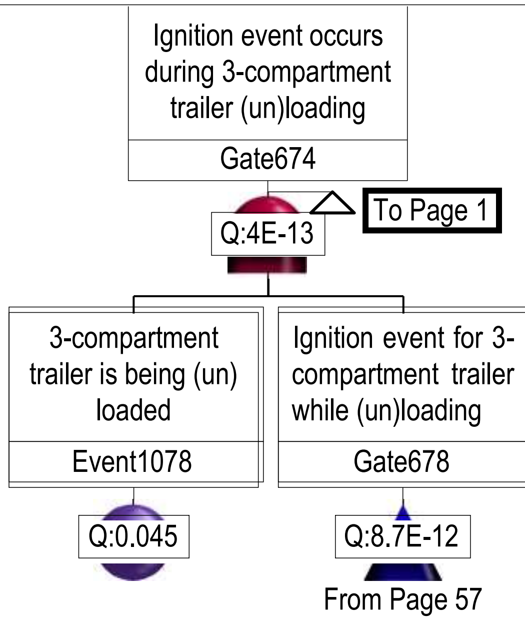
Ignition event occurs during 3-compartment trailer (un)loading
Gate674
Q:4E-13
To Page 1
3-compartment trailer is being (un) loaded
Event1078
Q:0.045
Ignition event for 3-compartment trailer while (un)loading
Gate678
Q:8.7E-12
From Page 57

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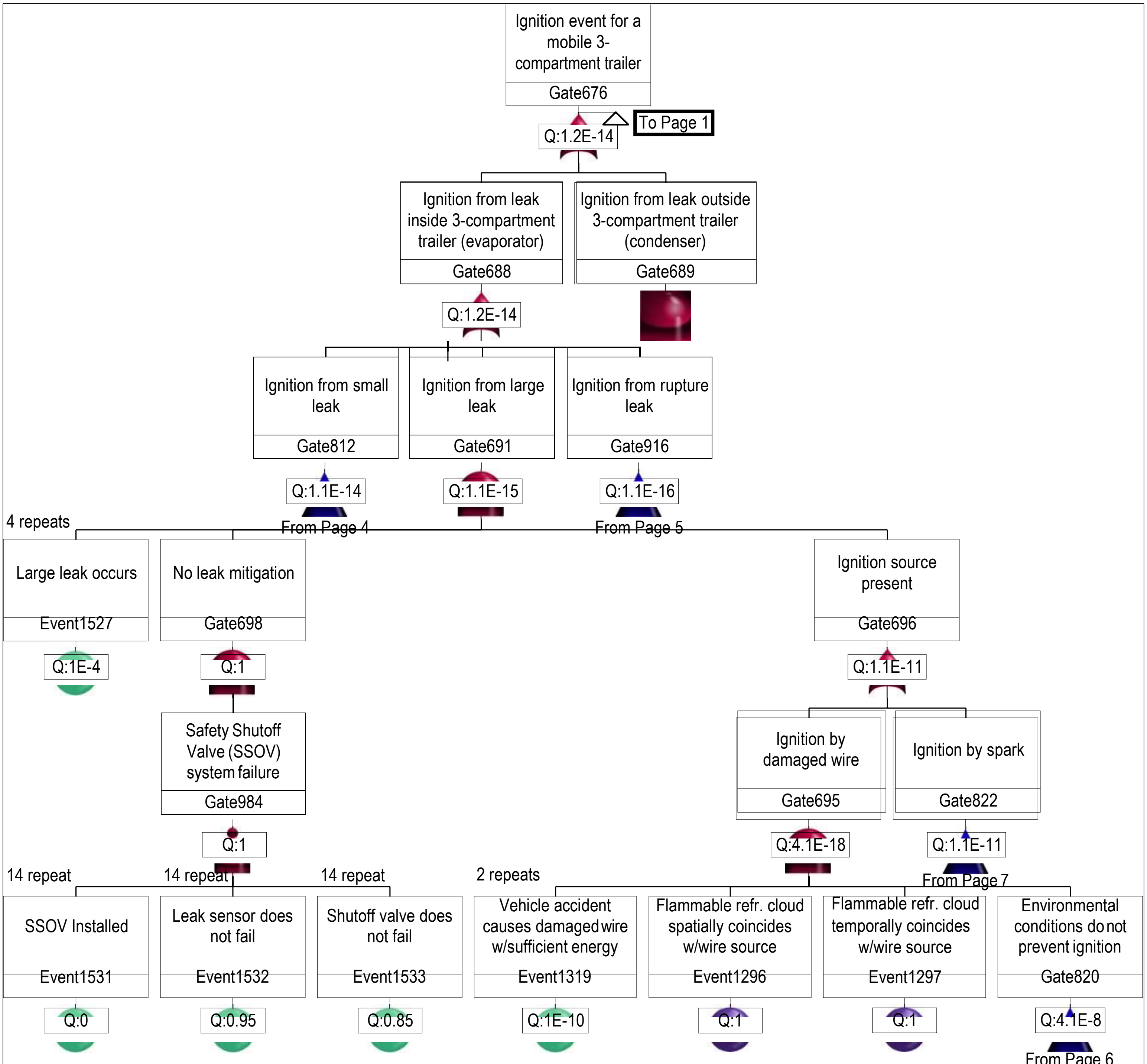

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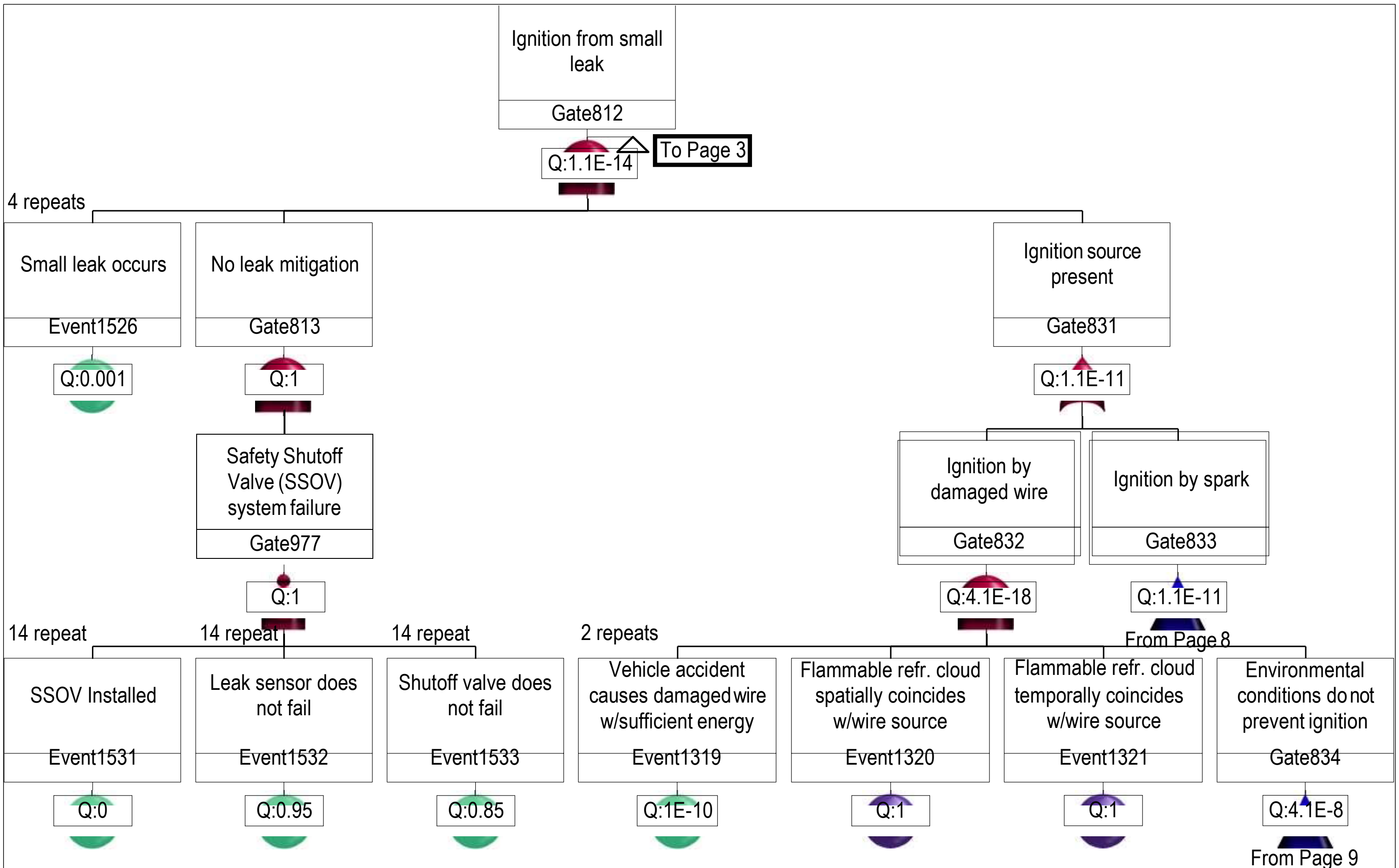
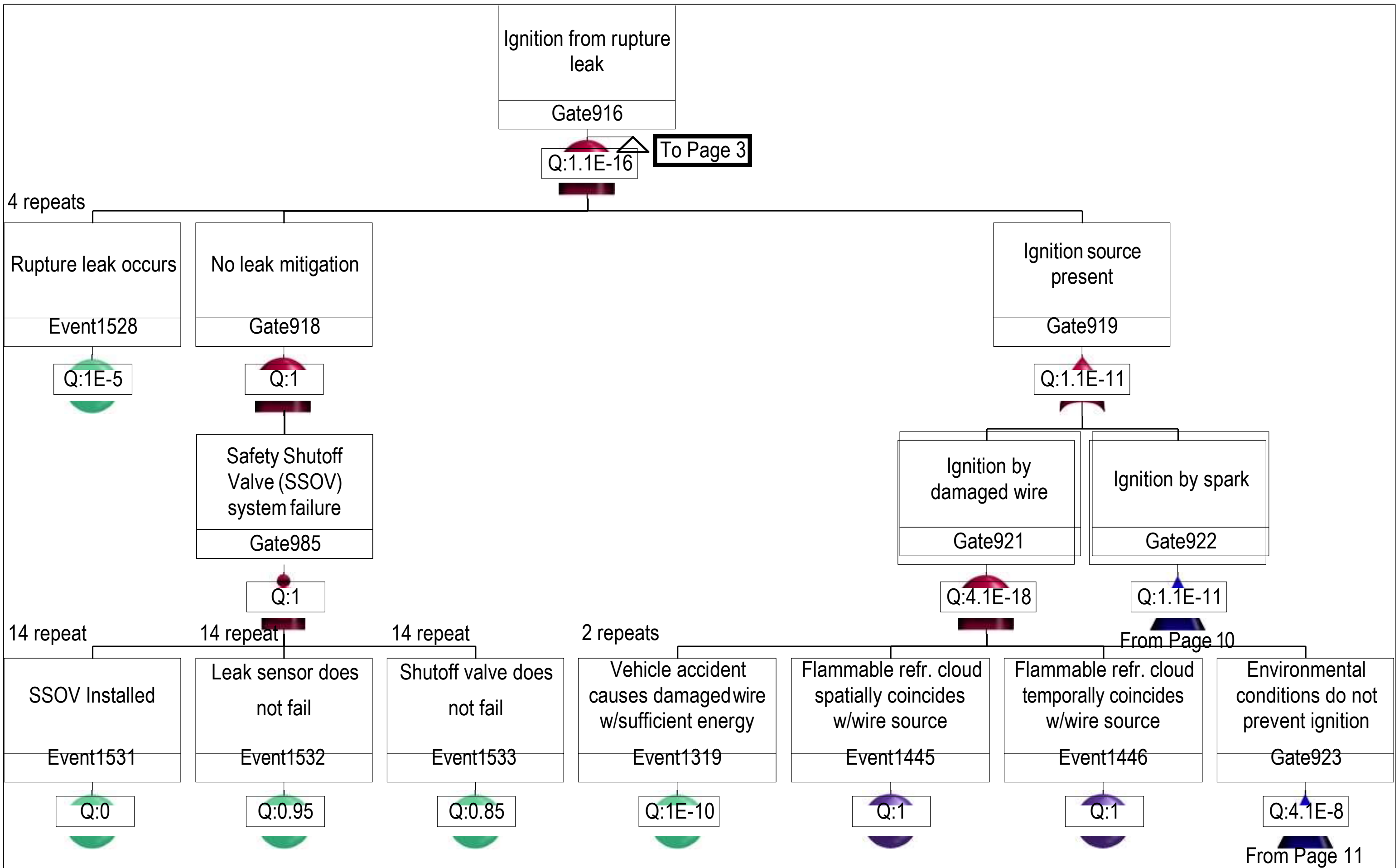
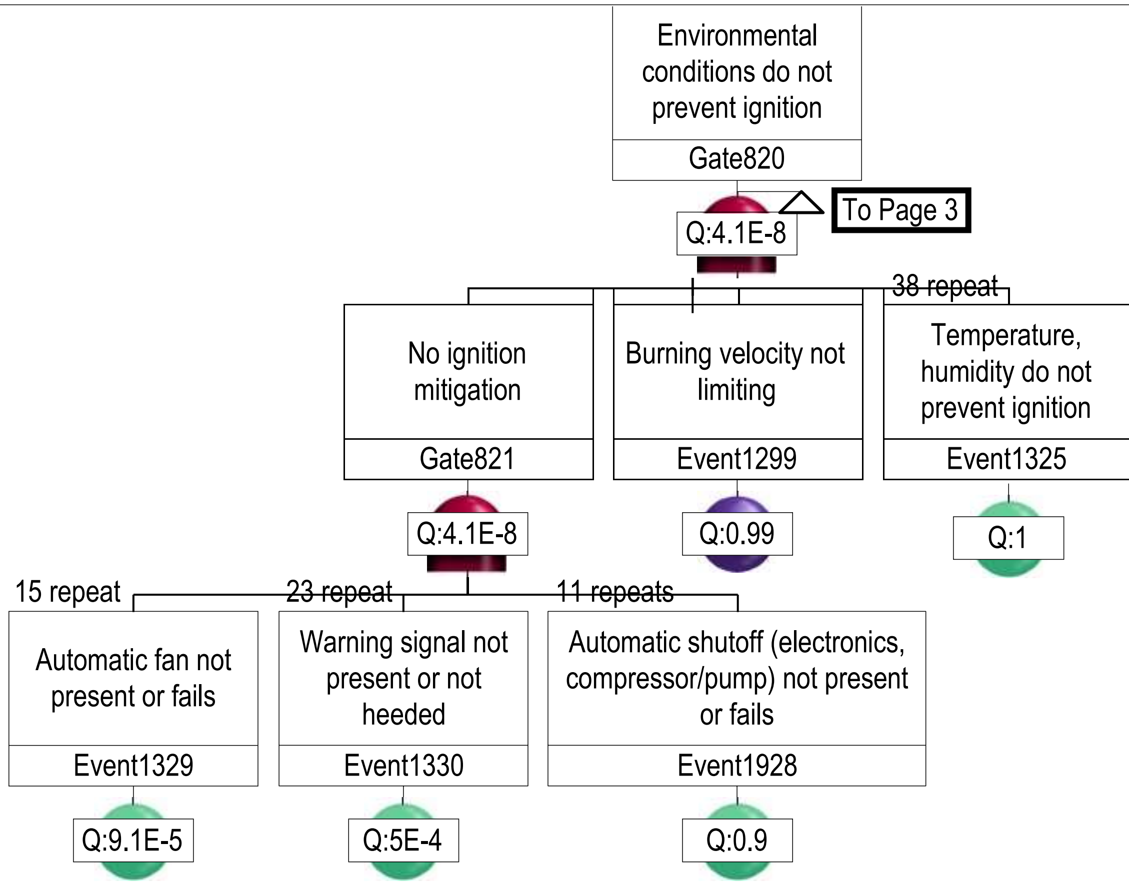
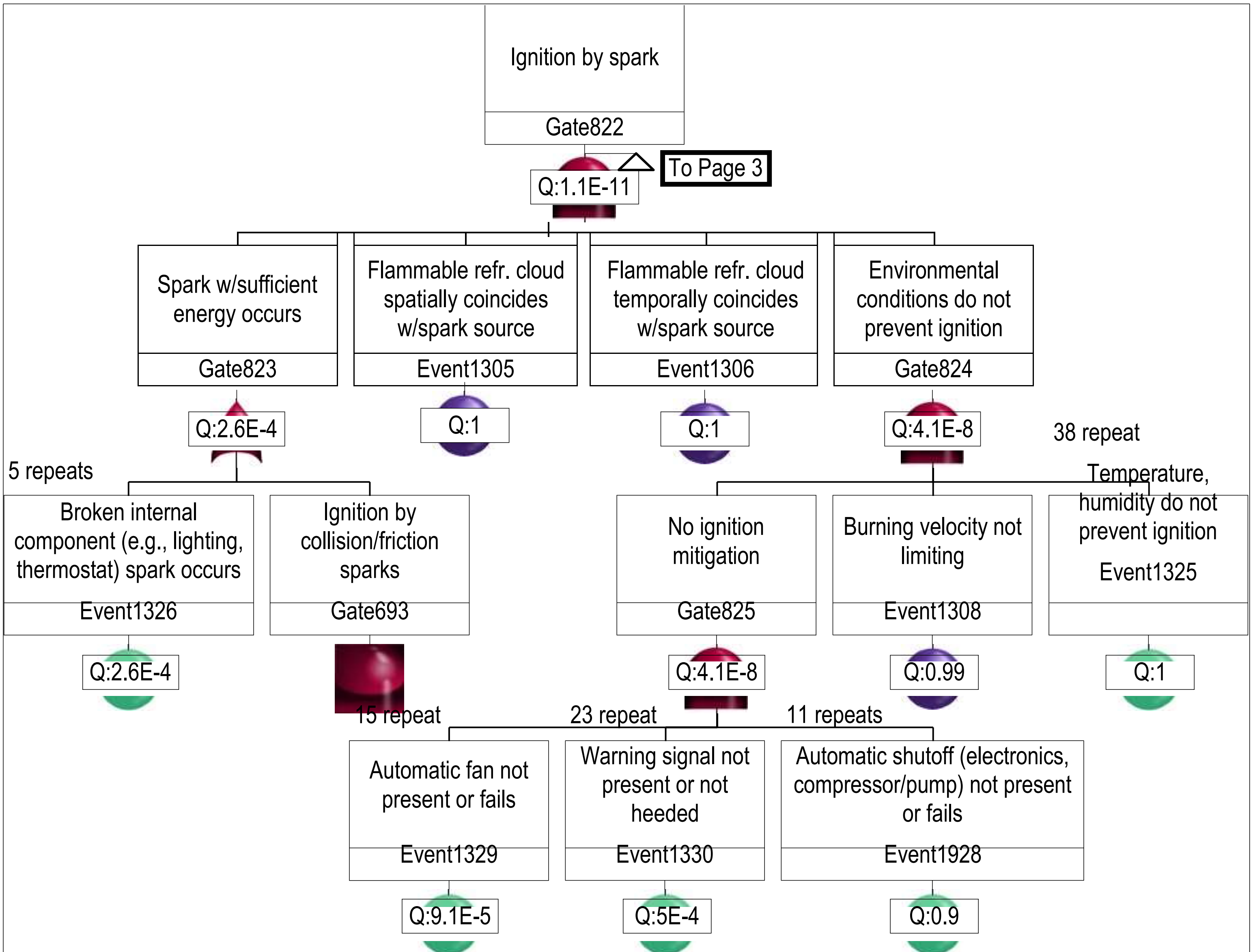
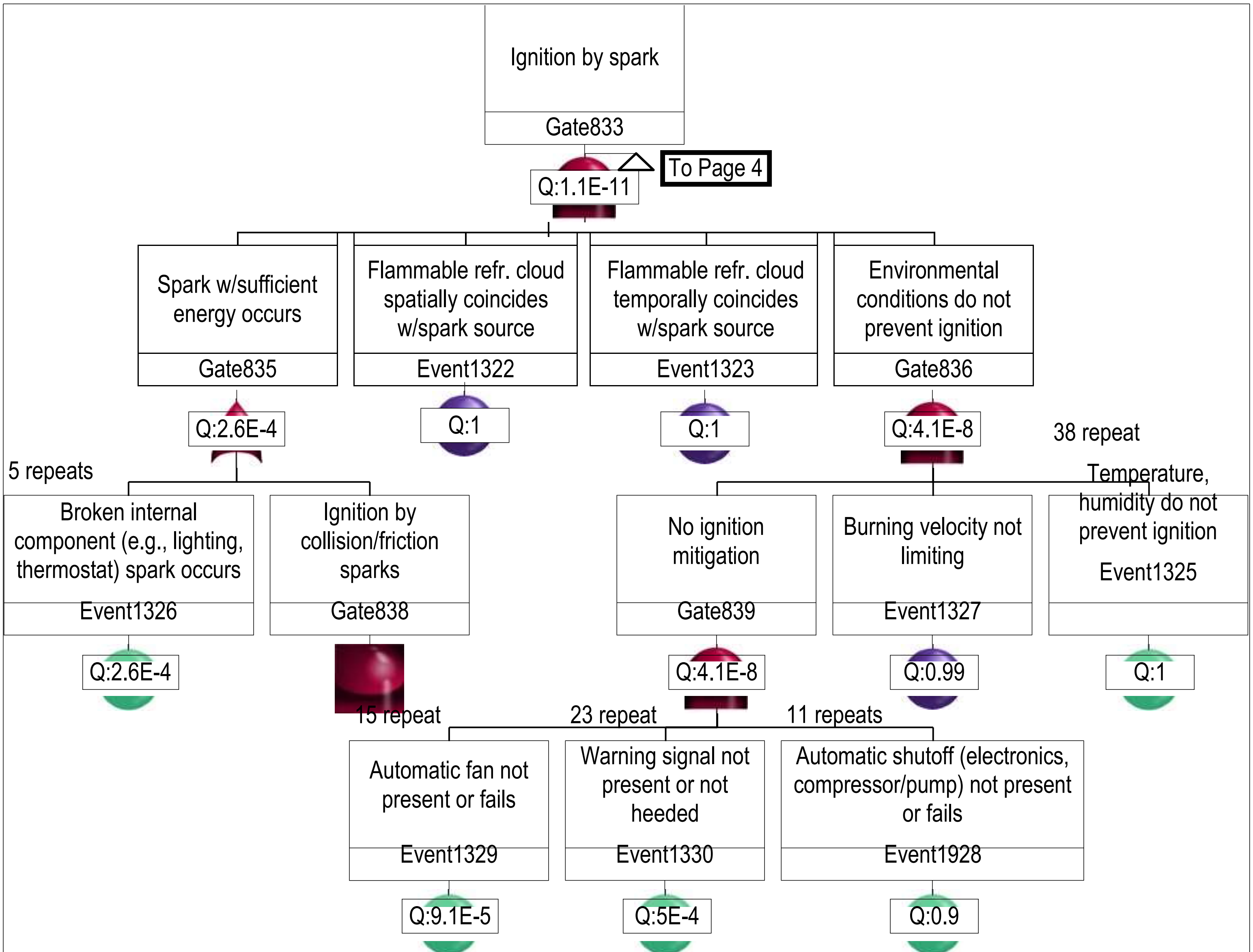



Ignition from rupture leak
Gate916
Q:1.1E-16
To Page 3
4 repeats
Rupture leak occurs
Event1528
Q:1E-5
No leak mitigation
Gate918
Q:1
Safety Shutoff Valve (SSOV) system failure
Gate985
Q:1
14 repeat
SSOV Installed
Event1531
Q:0
14 repeat
Leak sensor does not fail
Event1532
Q:0.95
14 repeat
Shutoff valve does not fail
Event1533
Q:0.85
Ignition source present
Gate919
Q:1.1E-11
Ignition by damaged wire
Gate921
Q:4.1E-18
Ignition by spark
Gate922
Q:1.1E-11
From Page 10
2 repeats
Vehicle accident causes damaged wire w/sufficient energy
Event1319
Q:1E-10
Flammable refr. cloud spatially coincides w/wire source
Event1445
Q:1
Flammable refr. cloud temporally coincides w/wire source
Event1446
Q:1
Environmental conditions do not prevent ignition
Gate923
Q:4.1E-8
From Page 11


Environmental conditions do not prevent ignition
Gate820
Q:4.1E-8
To Page 3
38 repeat
No ignition mitigation
Gate821
Q:4.1E-8
Burning velocity not limiting
Event1299
Q:0.99
Temperature, humidity do not prevent ignition
Event1325
Q:1
15 repeat
23 repeat
11 repeats
Automatic fan not present or fails
Event1329
Q:9.1E-5
Warning signal not present or not heeded
Event1330
Q:5E-4
Automatic shutoff (electronics, compressor/pump) not present or fails
Event1928
Q:0.9


Ignition by spark
Gate822
Q:1.1E-11
To Page 3
Spark w/sufficient energy occurs
Gate823
Q:2.6E-4
Flammable refr. cloud spatially coincides w/spark source
Event1305
Q:1
Flammable refr. cloud temporally coincides w/spark source
Event1306
Q:1
Environmental conditions do not prevent ignition
Gate824
Q:4.1E-8
38 repeat
5 repeats
Broken internal component (e.g., lighting, thermostat) spark occurs
Event1326
Q:2.6E-4
Ignition by collision/friction sparks
Gate693
No ignition mitigation
Gate825
Q:4.1E-8
Burning velocity not limiting
Event1308
Q:0.99
Temperature, humidity do not prevent ignition
Event1325
Q:1
15 repeat
23 repeat
11 repeats
Automatic fan not present or fails
Event1329
Q:9.1E-5
Warning signal not present or not heeded
Event1330
Q:5E-4
Automatic shutoff (electronics, compressor/pump) not present or fails
Event1928
Q:0.9


Ignition by spark
Gate833
Q:1.1E-11
To Page 4
Spark w/sufficient energy occurs
Gate835
Q:2.6E-4
Flammable refr. cloud spatially coincides w/spark source
Event1322
Q:1
Flammable refr. cloud temporally coincides w/spark source
Event1323
Q:1
Environmental conditions do not prevent ignition
Gate836
Q:4.1E-8
38 repeat
5 repeats
Broken internal component (e.g., lighting, thermostat) spark occurs
Event1326
Q:2.6E-4
Ignition by collision/friction sparks
Gate838
No ignition mitigation
Gate839
Q:4.1E-8
Burning velocity not limiting
Event1327
Q:0.99
Temperature, humidity do not prevent ignition
Event1325
Q:1
15 repeat
23 repeat
11 repeats
Automatic fan not present or fails
Event1329
Q:9.1E-5
Warning signal not present or not heeded
Event1330
Q:5E-4
Automatic shutoff (electronics, compressor/pump) not present or fails
Event1928
Q:0.9

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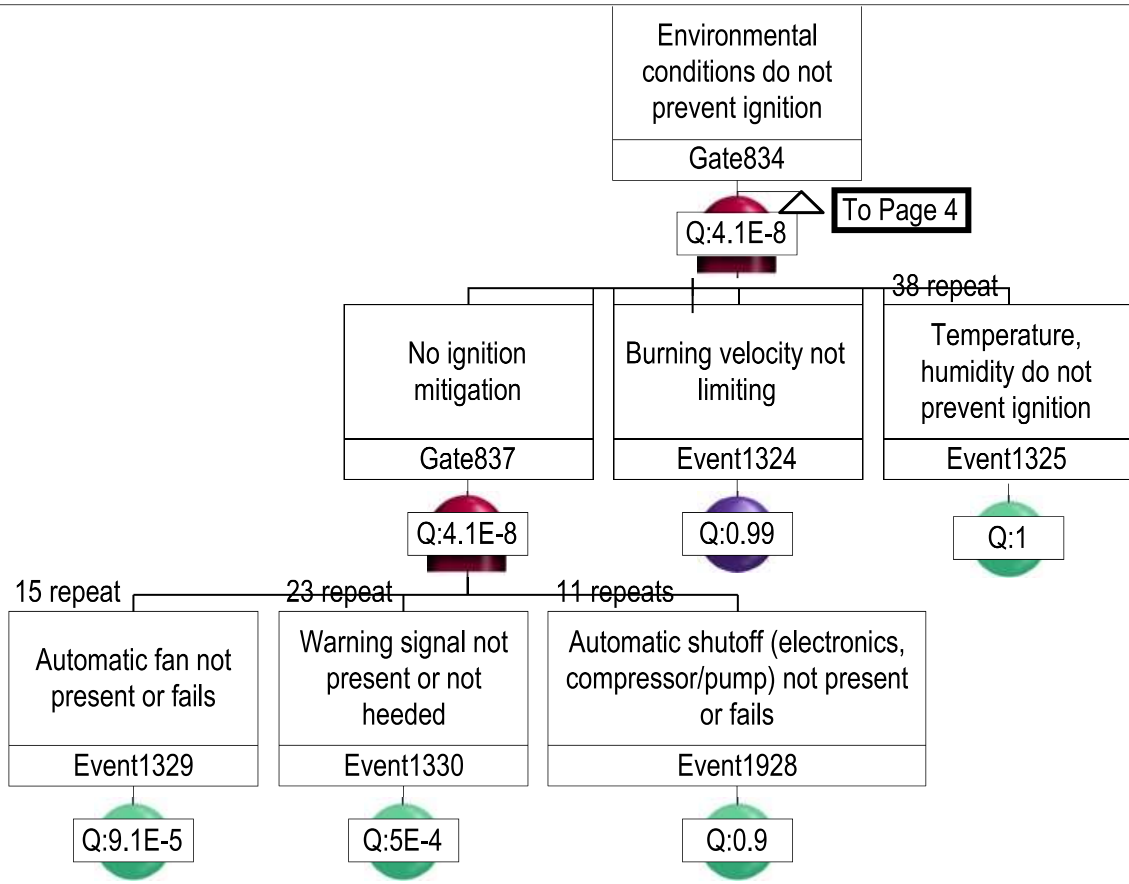
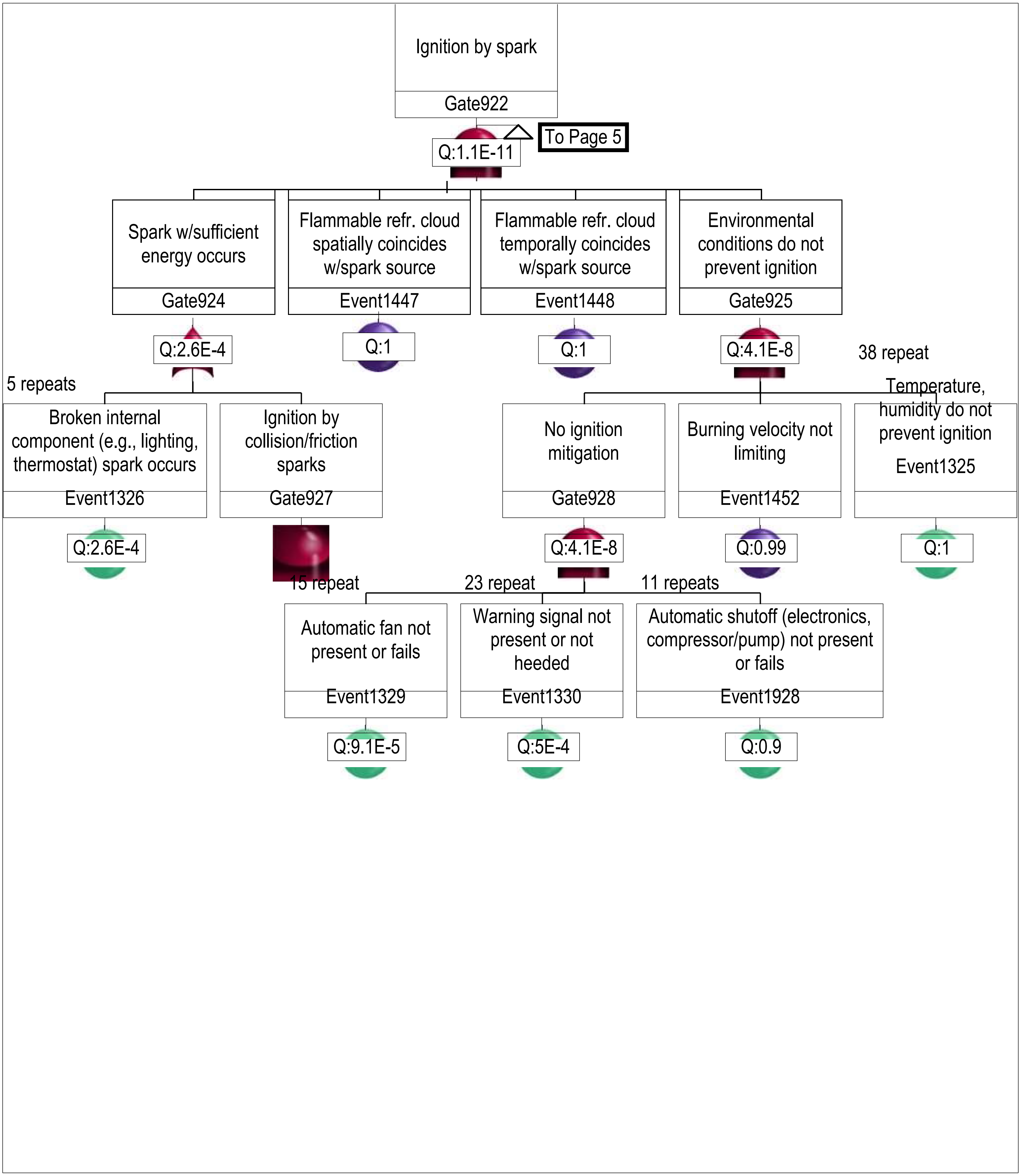
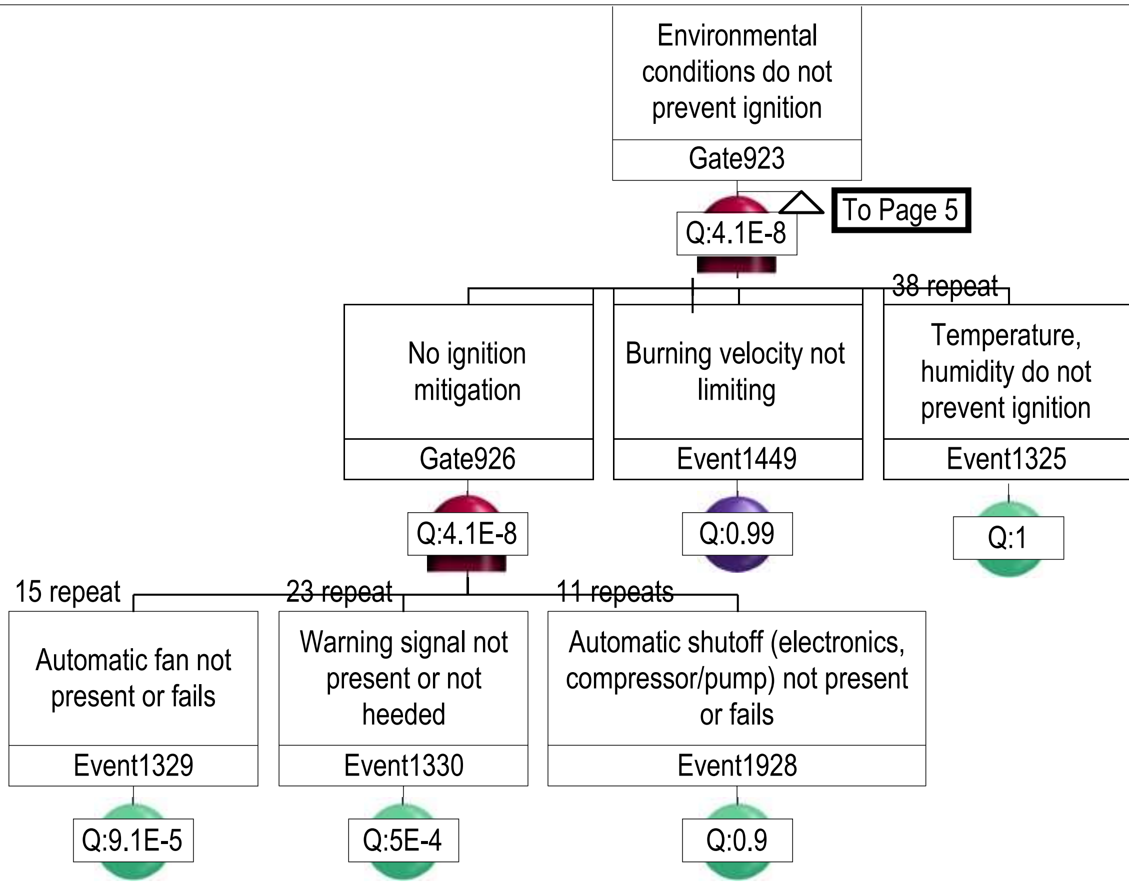
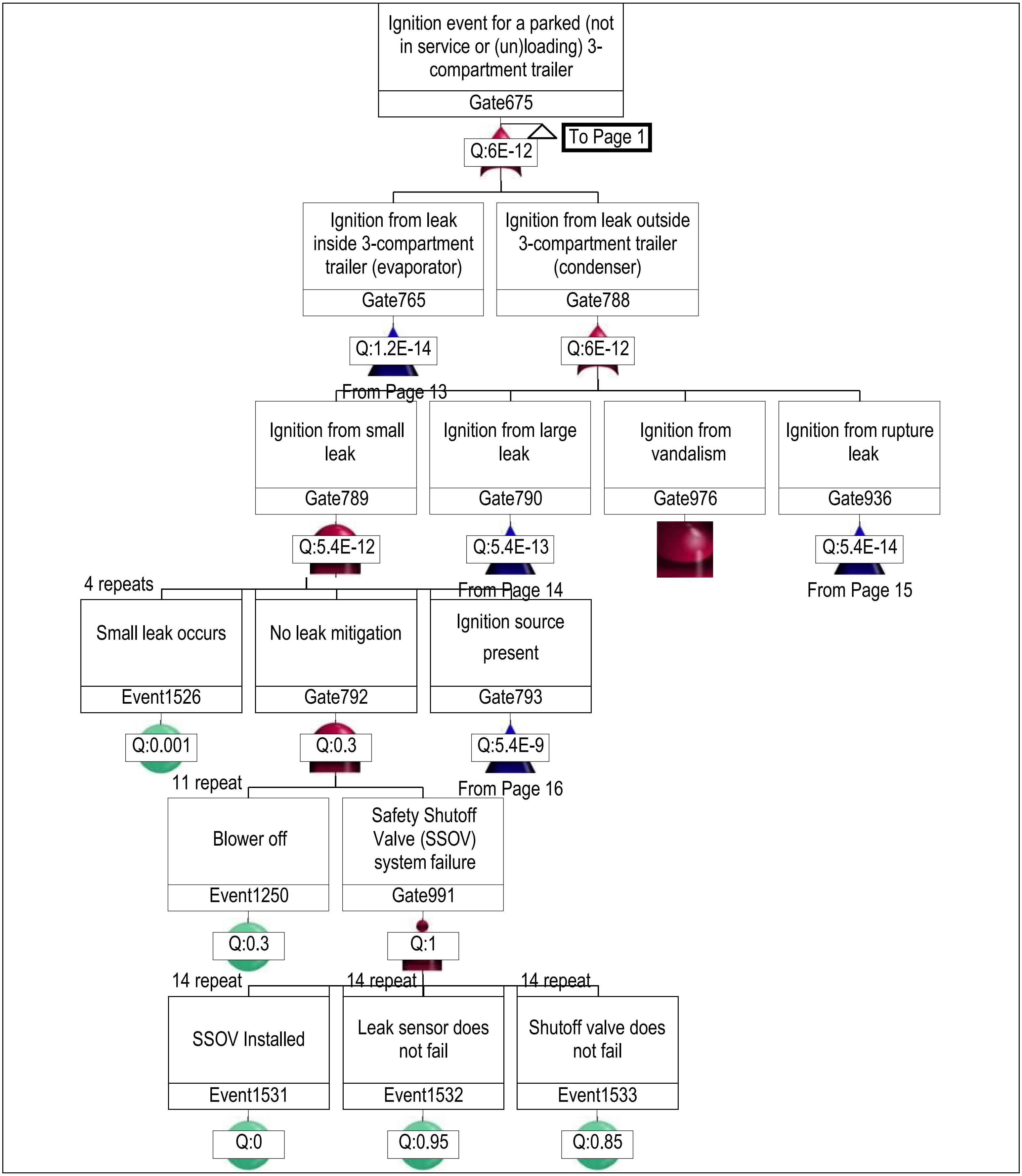



Ignition by spark
Gate922
Q:1.1E-11
To Page 5
Spark w/sufficient energy occurs
Gate924
Q:2.6E-4
Flammable refr. cloud spatially coincides w/spark source
Event1447
Q:1
Flammable refr. cloud temporally coincides w/spark source
Event1448
Q:1
Environmental conditions do not prevent ignition
Gate925
Q:4.1E-8
38 repeat
5 repeats
Broken internal component (e.g., lighting, thermostat) spark occurs
Event1326
Q:2.6E-4
Ignition by collision/friction sparks
Gate927
No ignition mitigation
Gate928
Q:4.1E-8
Burning velocity not limiting
Event1452
Q:0.99
Temperature, humidity do not prevent ignition
Event1325
Q:1
15 repeat
23 repeat
11 repeats
Automatic fan not present or fails
Event1329
Q:9.1E-5
Warning signal not present or not heeded
Event1330
Q:5E-4
Automatic shutoff (electronics, compressor/pump) not present or fails
Event1928
Q:0.9


Environmental conditions do not prevent ignition
Gate923
Q:4.1E-8
To Page 5
38 repeat
No ignition mitigation
Gate926
Burning velocity not limiting
Event1449
Temperature, humidity do not prevent ignition
Event1325
Q:4.1E-8
Q:0.99
Q:1
15 repeat
23 repeat
11 repeats
Automatic fan not present or fails
Event1329
Warning signal not present or not heeded
Event1330
Automatic shutoff (electronics, compressor/pump) not present or fails
Event1928
Q:9.1E-5
Q:5E-4
Q:0.9

File Name: AHRI-3c-trailer.RFP



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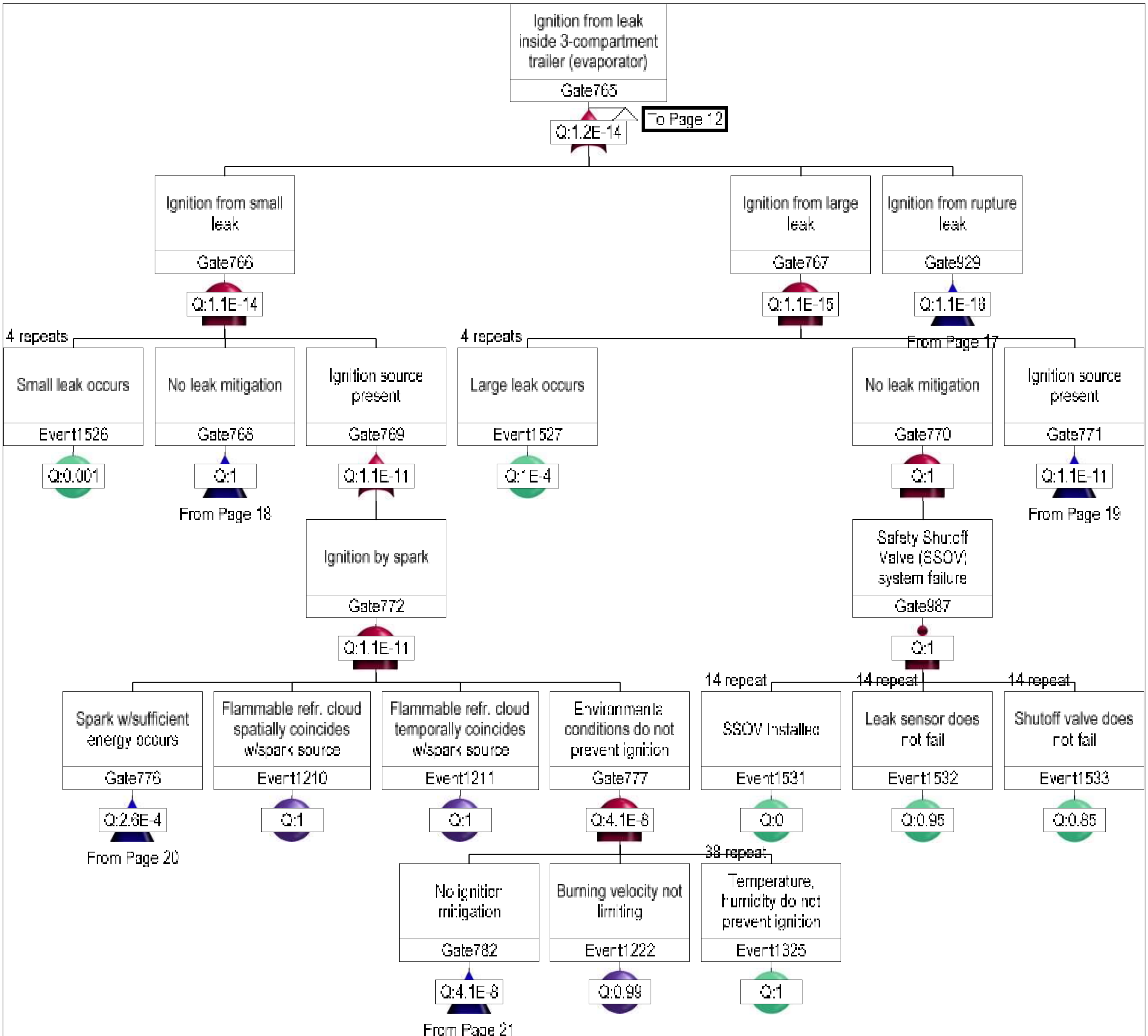
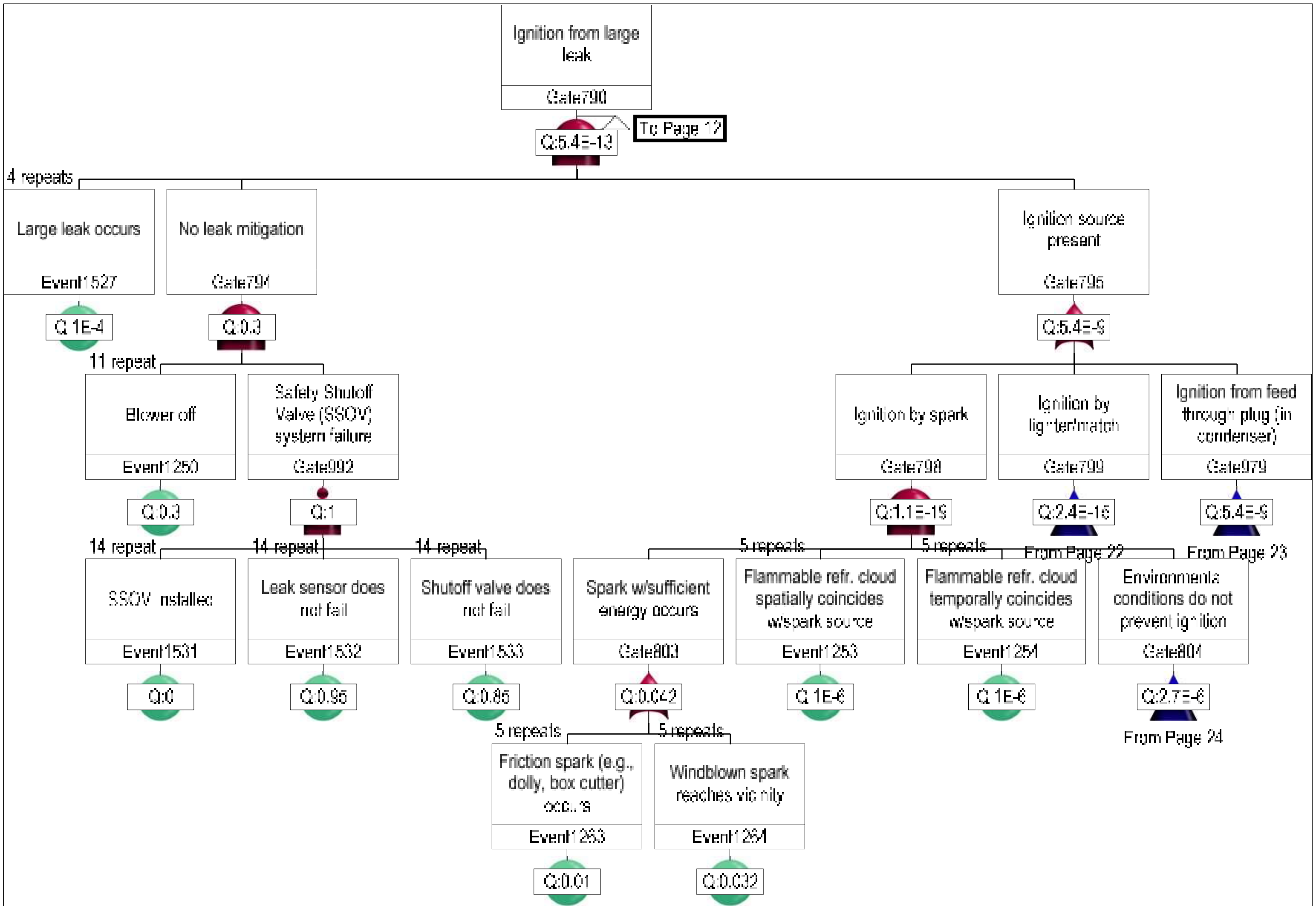

Ignition from leak inside 3-compartment trailer (evaporator)
Gate765
Q:1.2E-14
To Page 12
Ignition from small leak
Gate766
Q:1.1E-14
Ignition from large leak
Gate767
Q:1.1E-15
Ignition from rupture leak
Gate929
Q:1.1E-18
From Page 17
4 repeats
Small leak occurs
Event1526
Q:0.001
No leak mitigation
Gate768
Q:1
From Page 18
Ignition source present
Gate769
Q:1.1E-11
4 repeats
Large leak occurs
Event1527
Q:1E-4
No leak mitigation
Gate770
Q:1
Ignition source present
Gate771
Q:1.1E-11
From Page 19
Ignition by spark
Gate772
Q:1.1E-11
Safety Shutoff Valve (SSOV) system failure
Gate987
Q:1
Spark w/sufficient energy occurs
Gate776
Q:2.6E-4
From Page 20
Flammable refr. cloud spatially coincides w/spark source
Event1210
Q:1
Flammable refr. cloud temporally coincides w/spark source
Event1211
Q:1
Environmental conditions do not prevent ignition
Gate777
Q:4.1E-8
14 repeat
SSOV Installed
Event1531
Q:0
14 repeat
Leak sensor does not fail
Event1532
Q:0.95
14 repeat
Shutoff valve does not fail
Event1533
Q:0.85
38 repeat
No ignition mitigation
Gate782
Q:4.1E-8
From Page 21
Burning velocity not limiting
Event1222
Q:0.99
Temperature, humidity do not prevent ignition
Event1325
Q:1

File Name: AHRI-3c-trailer.RFP



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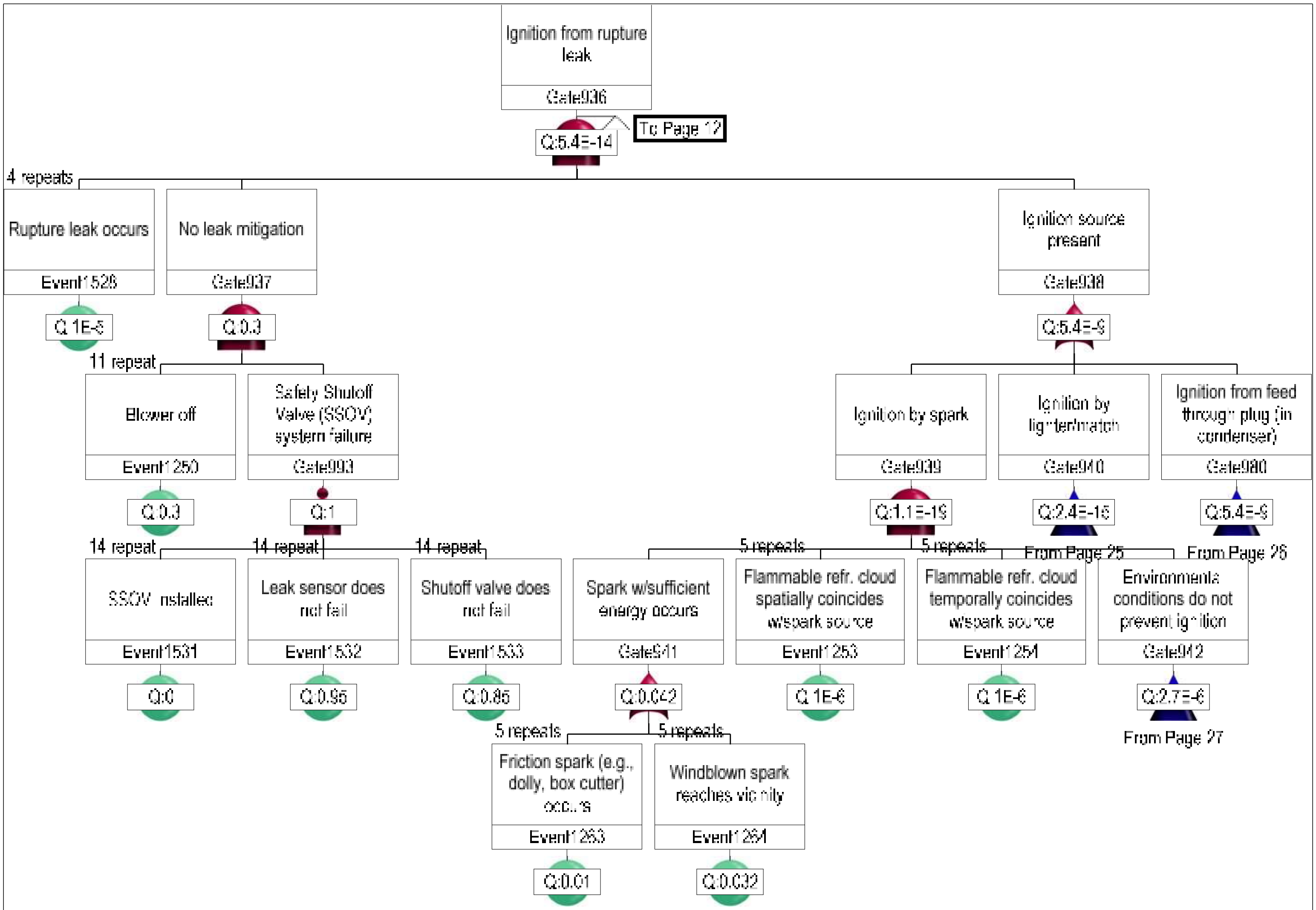

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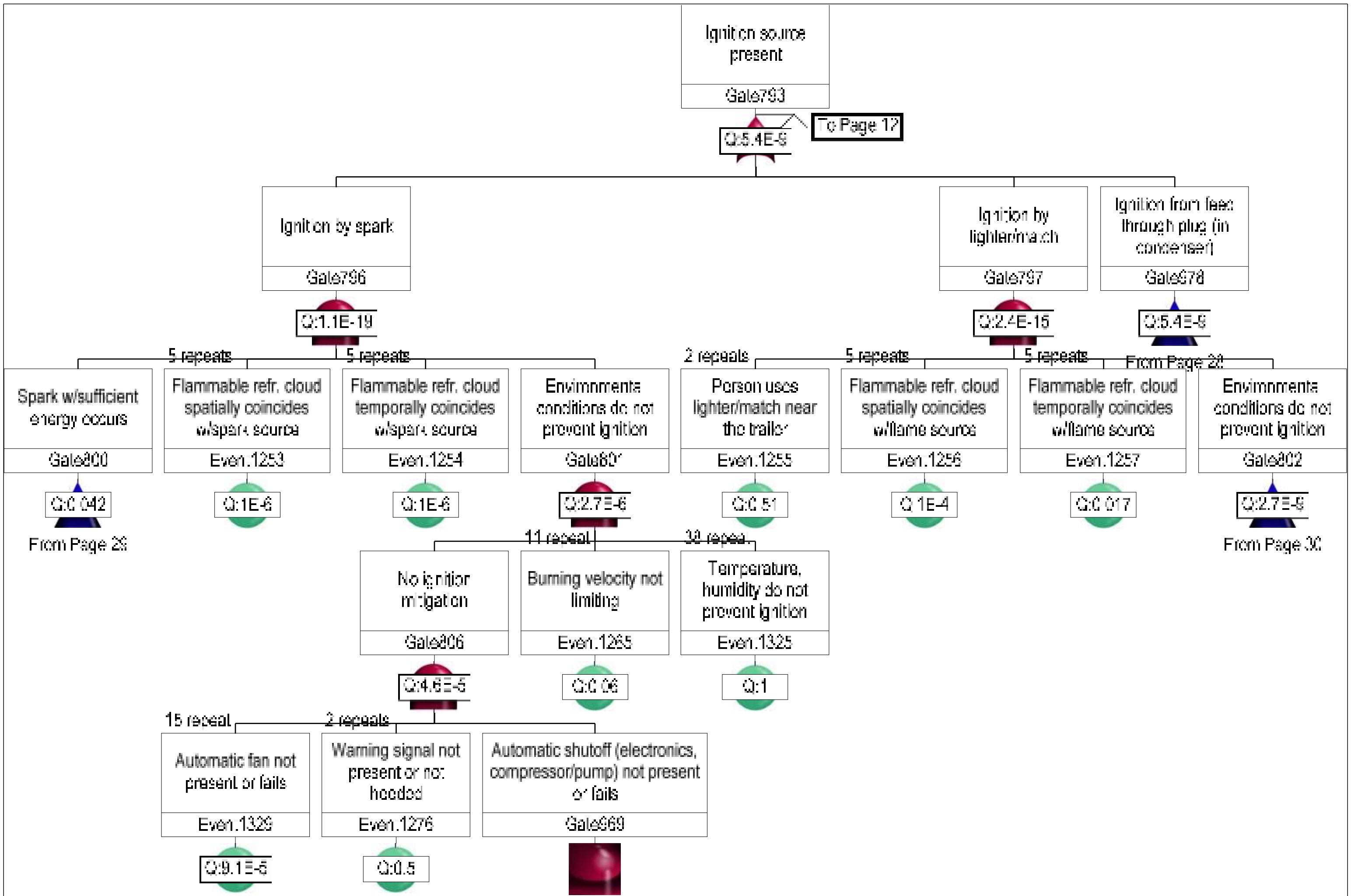

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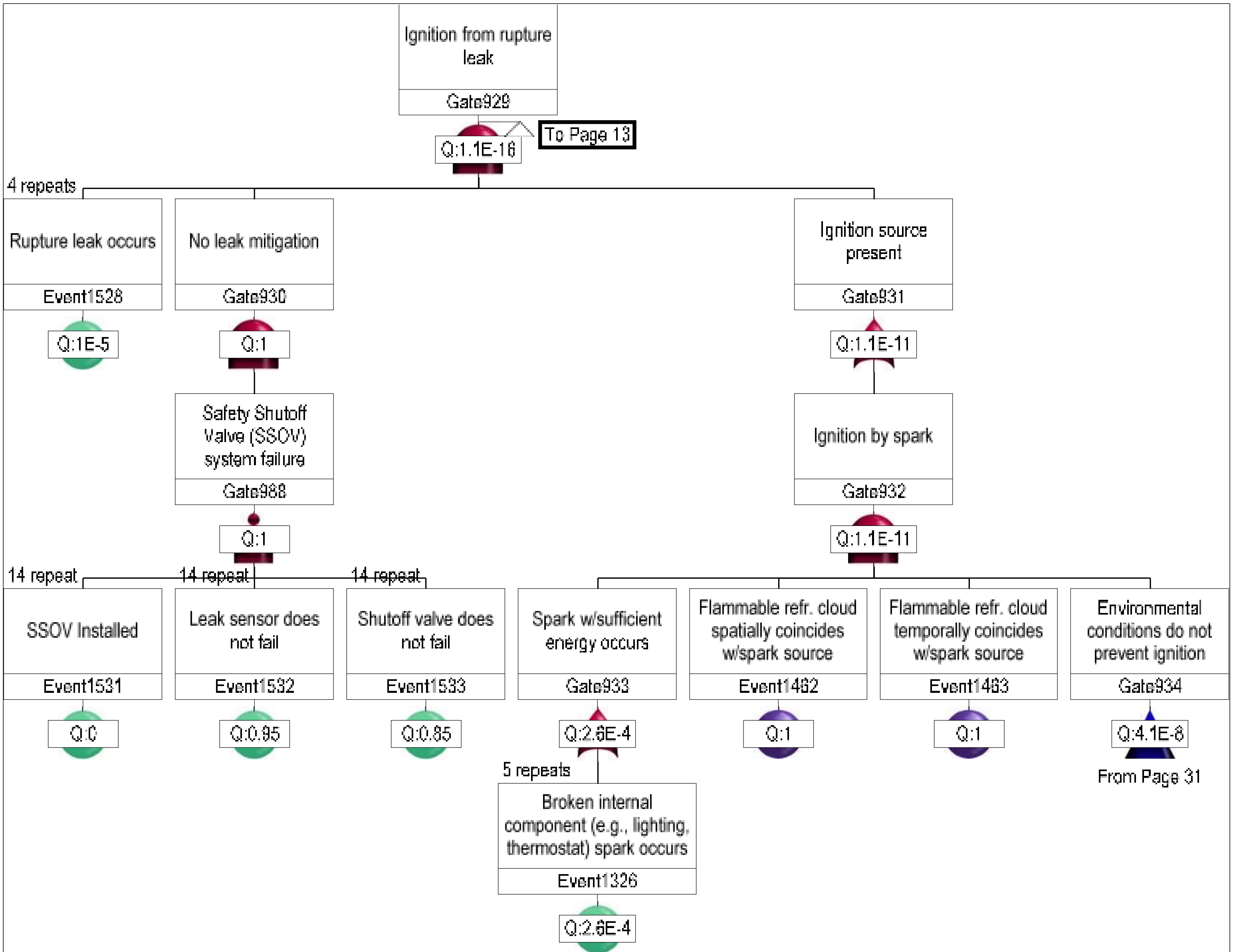

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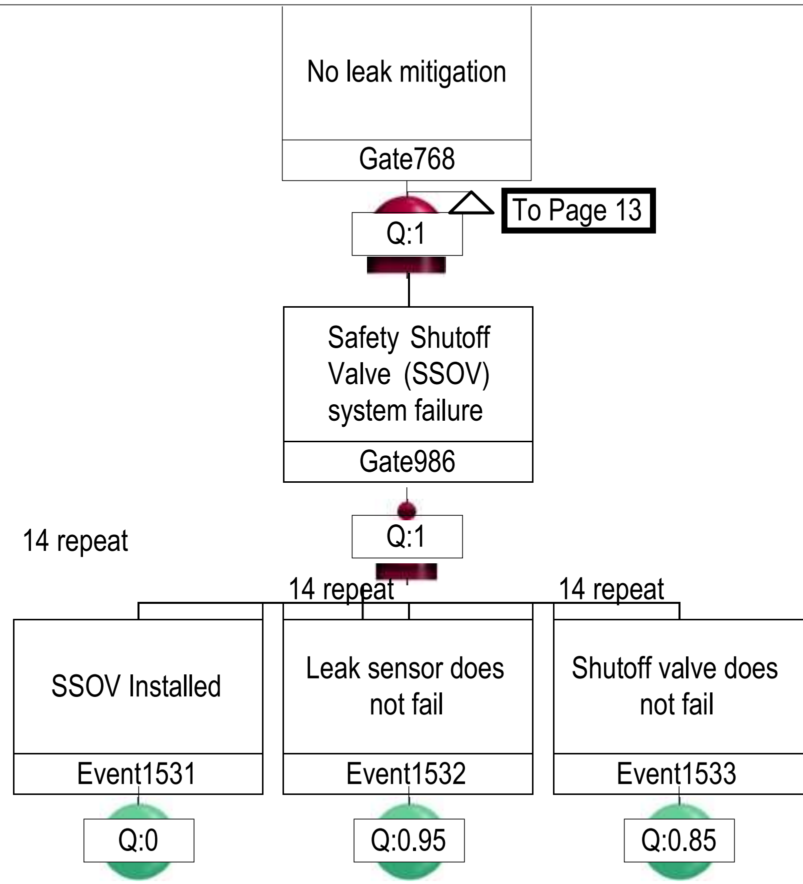

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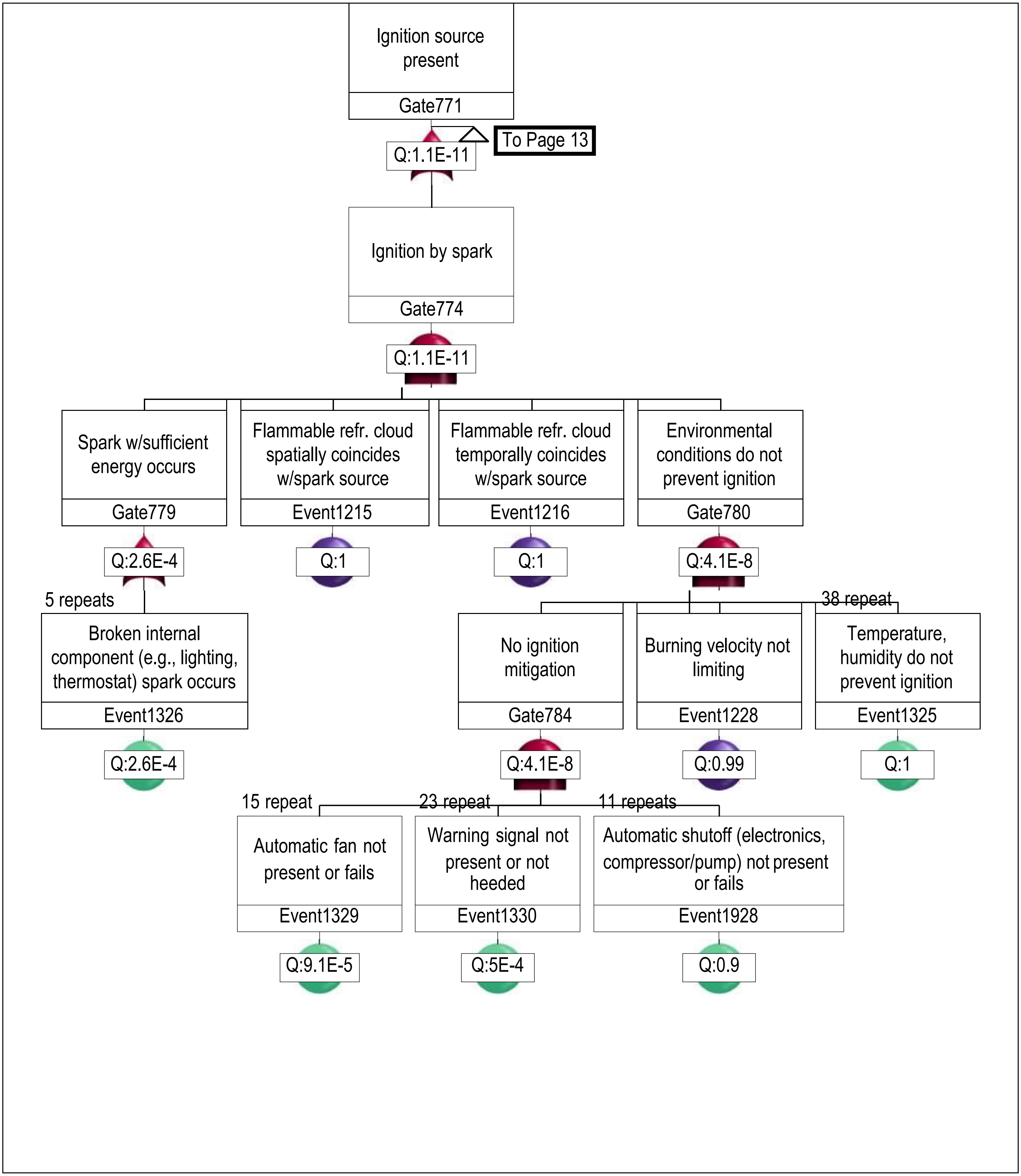
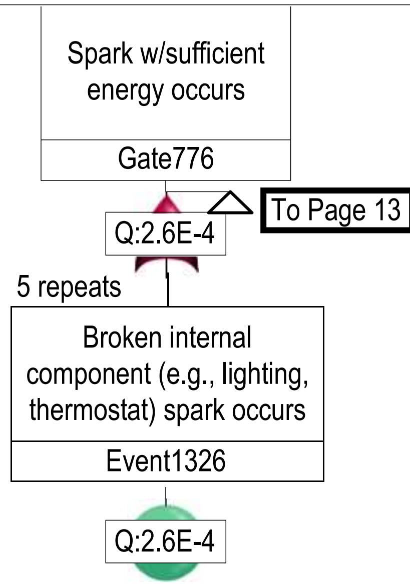
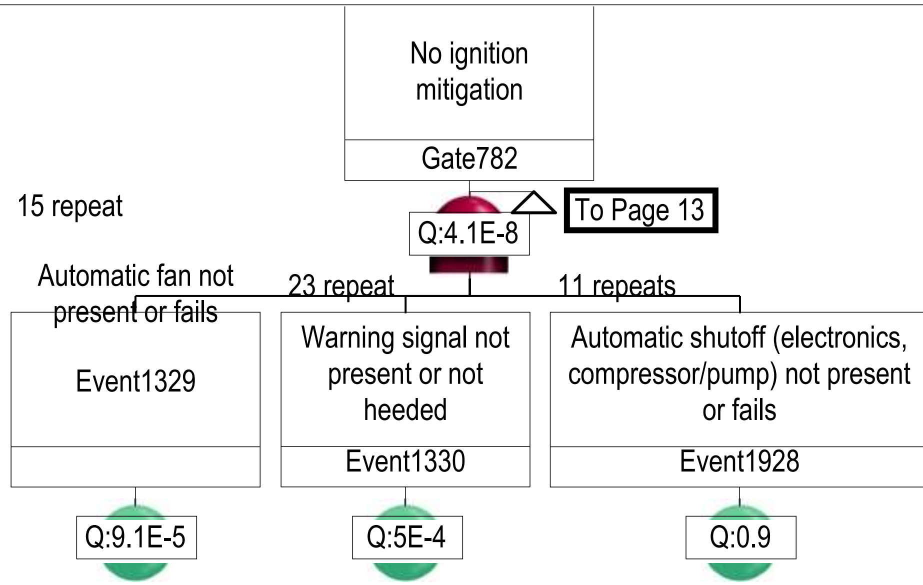
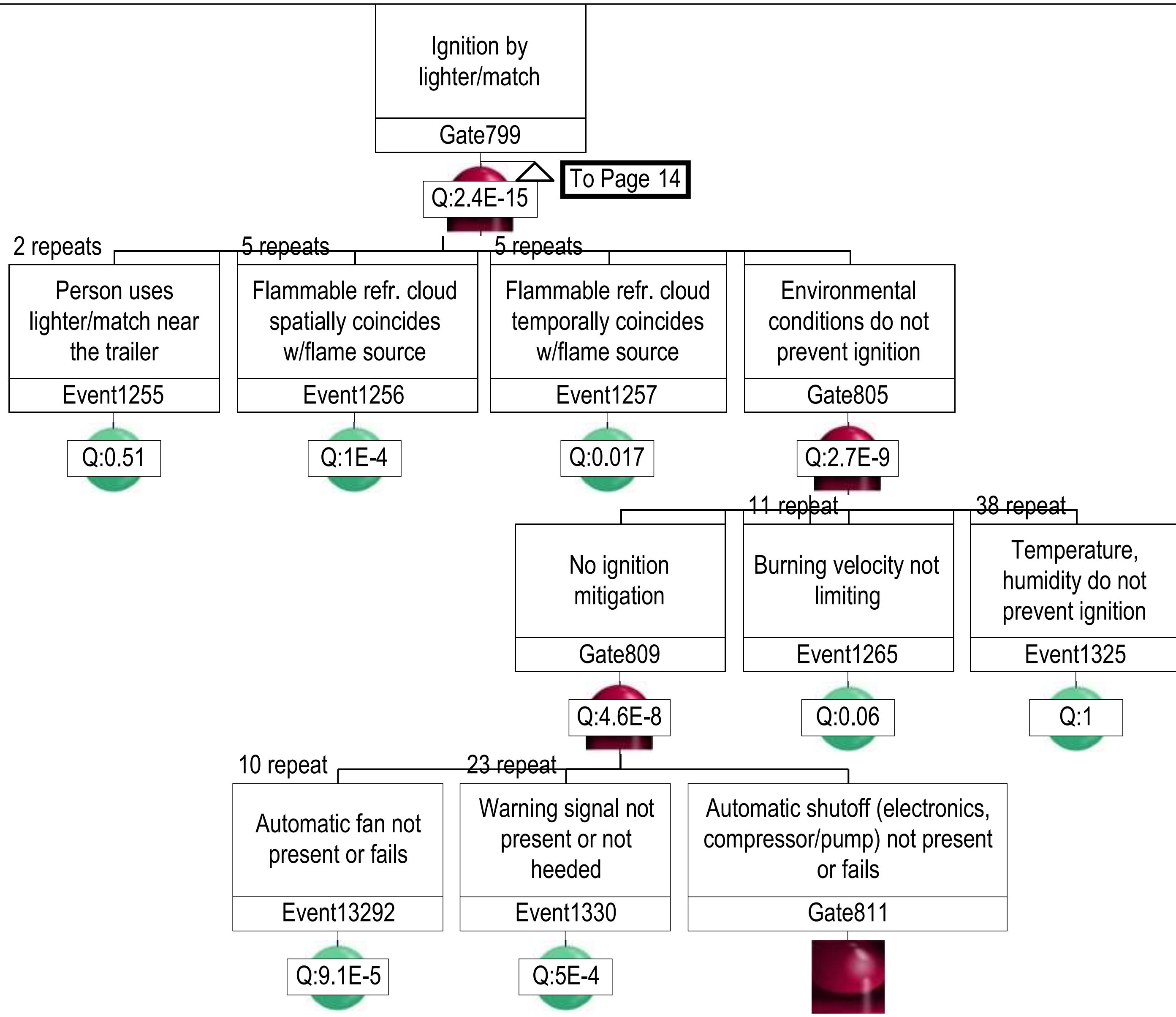



Spark w/sufficient energy occurs
Gate776
Q:2.6E-4
To Page 13
5 repeats
Broken internal component (e.g., lighting, thermostat) spark occurs
Event1326
Q:2.6E-4


No ignition mitigation
Gate782
15 repeat
Q:4.1E-8
To Page 13
Automatic fan not present or fails
23 repeat
11 repeats
Event1329
Warning signal not present or not heeded
Event1330
Automatic shutoff (electronics, compressor/pump) not present or fails
Event1928
Q:9.1E-5
Q:5E-4
Q:0.9

File Name: AHRI-3c-trailer.RFP



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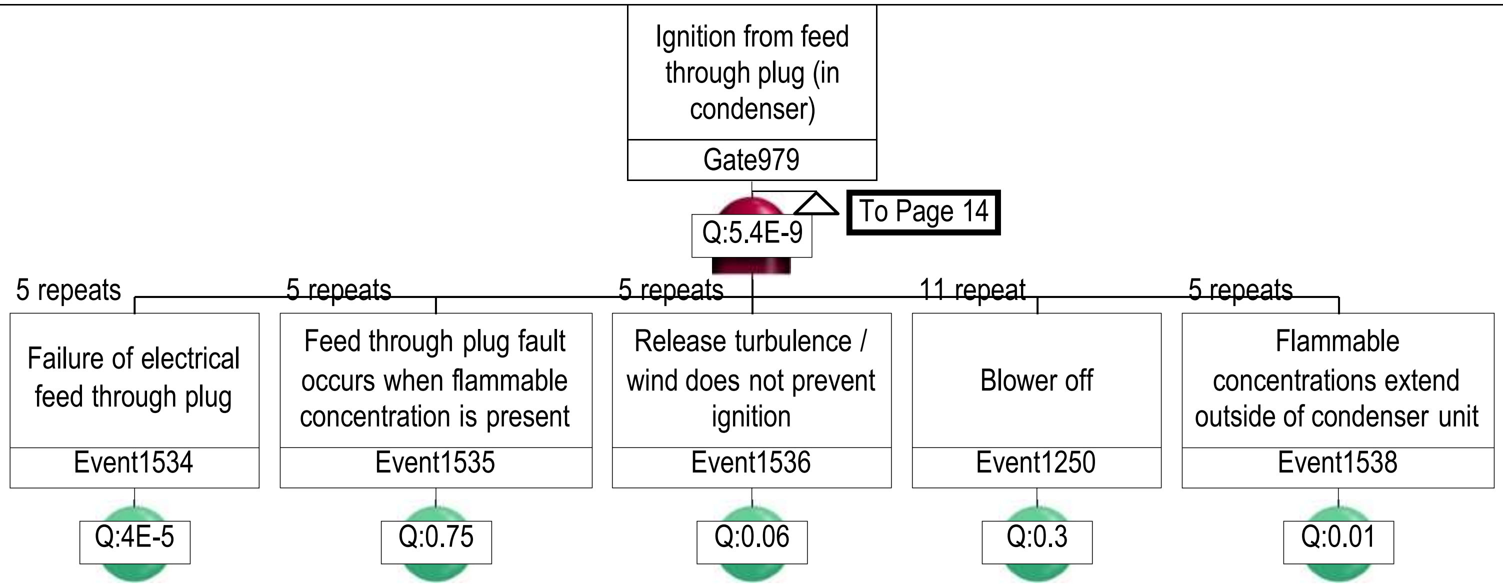
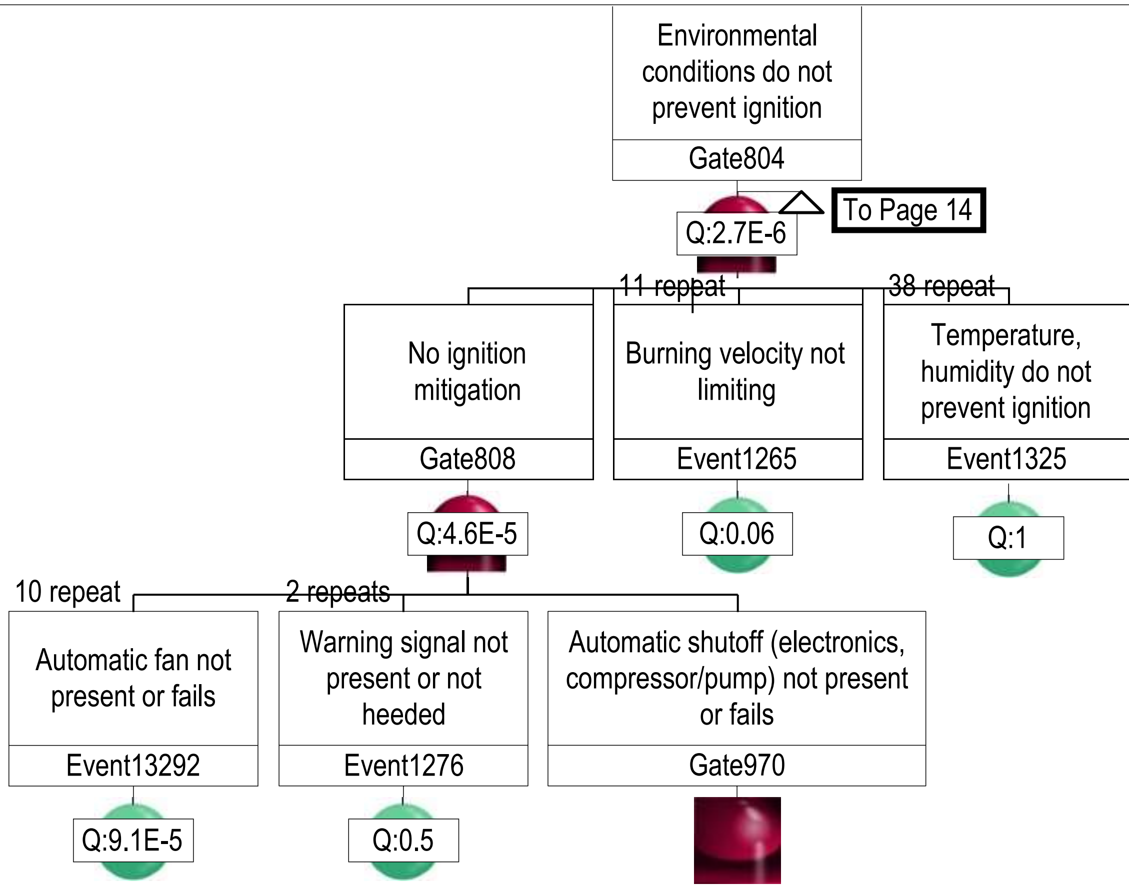
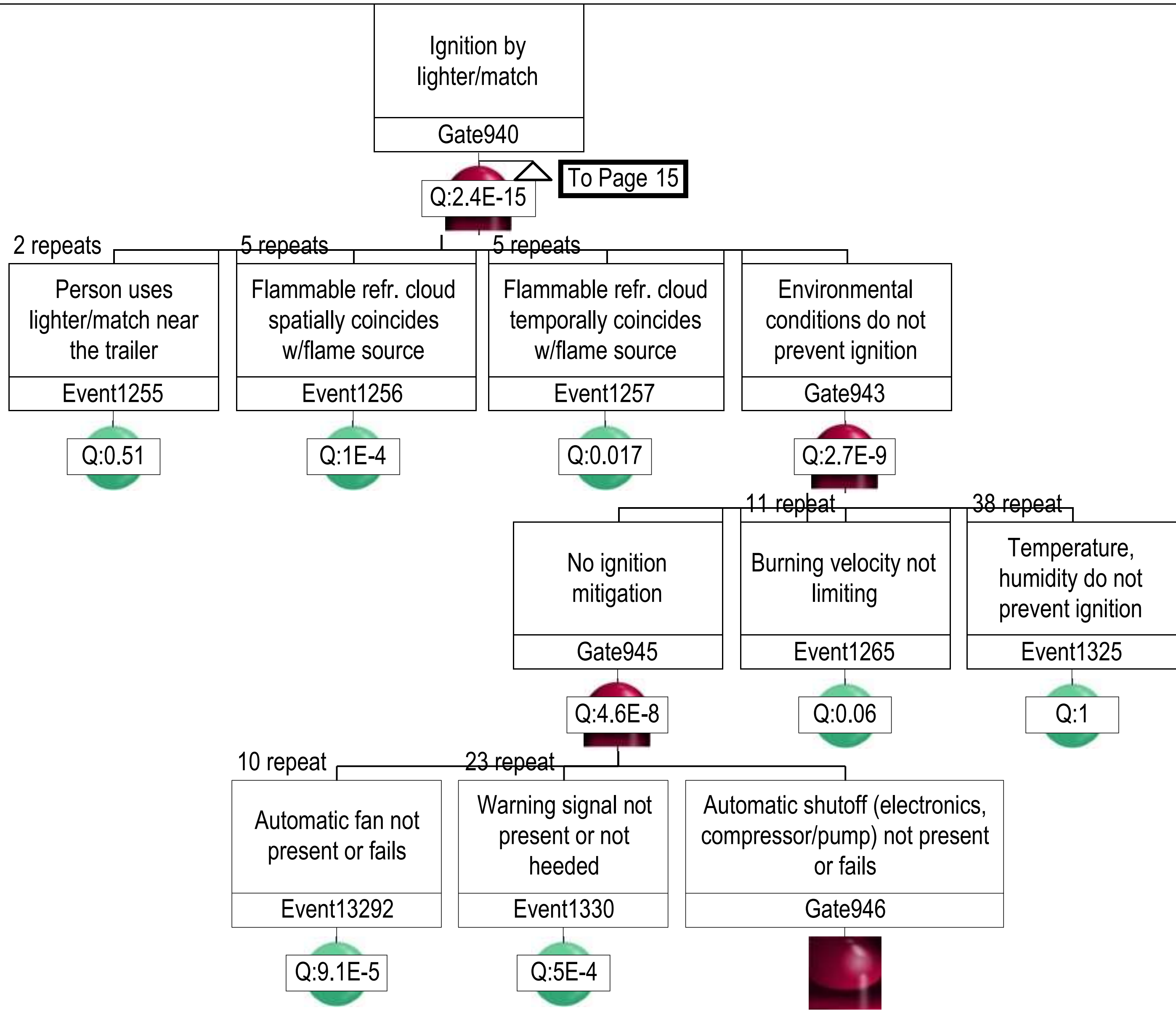



Environmental conditions do not prevent ignition
Gate804
Q:2.7E-6
To Page 14
11 repeat
38 repeat
No ignition mitigation
Gate808
Burning velocity not limiting
Event1265
Temperature, humidity do not prevent ignition
Event1325
Q:4.6E-5
Q:0.06
Q:1
10 repeat
2 repeats
Automatic fan not present or fails
Event13292
Warning signal not present or not heeded
Event1276
Automatic shutoff (electronics, compressor/pump) not present or fails
Gate970
Q:9.1E-5
Q:0.5

File Name: AHRI-3c-trailer.RFP



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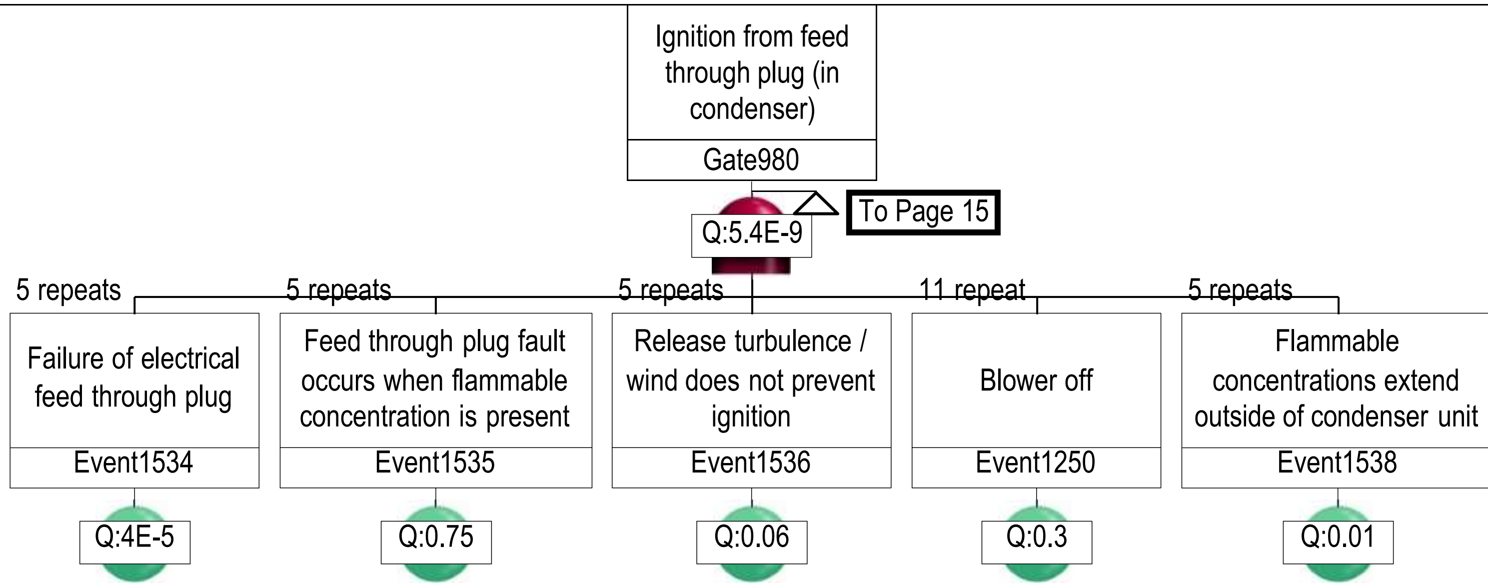
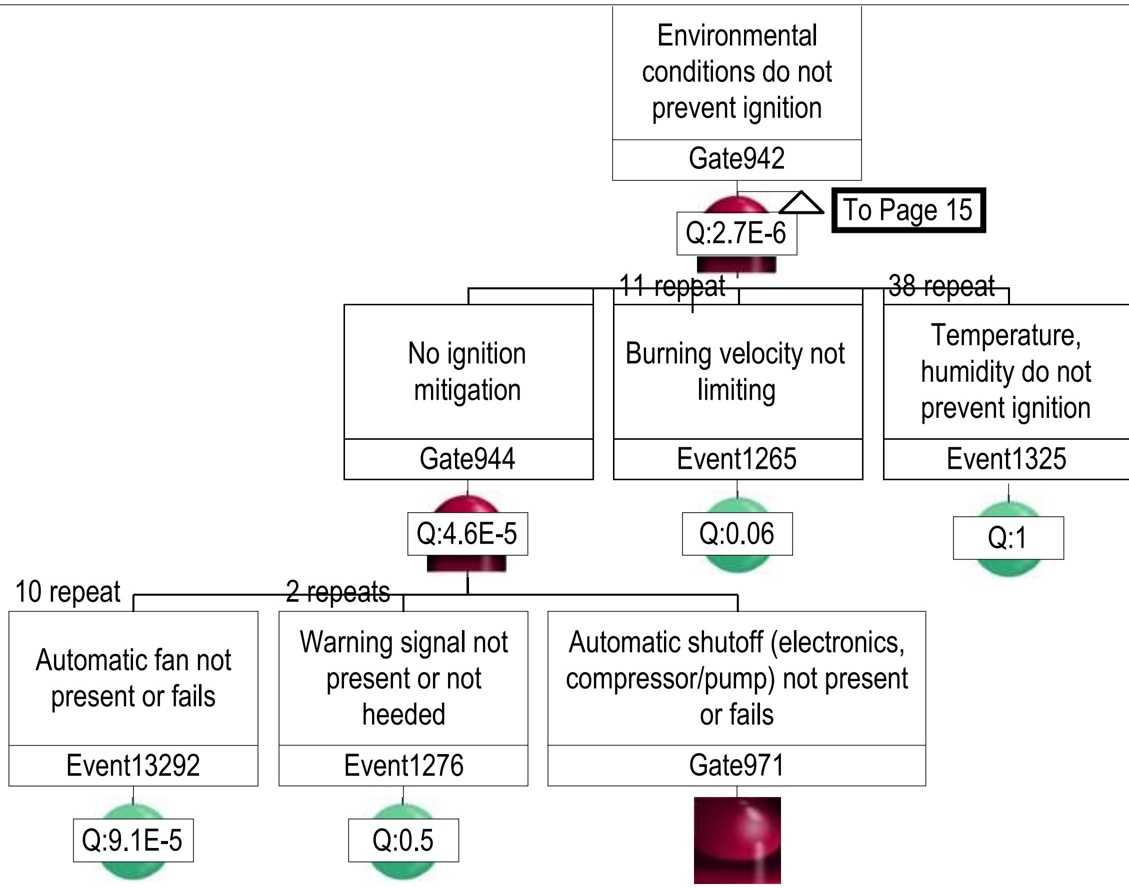
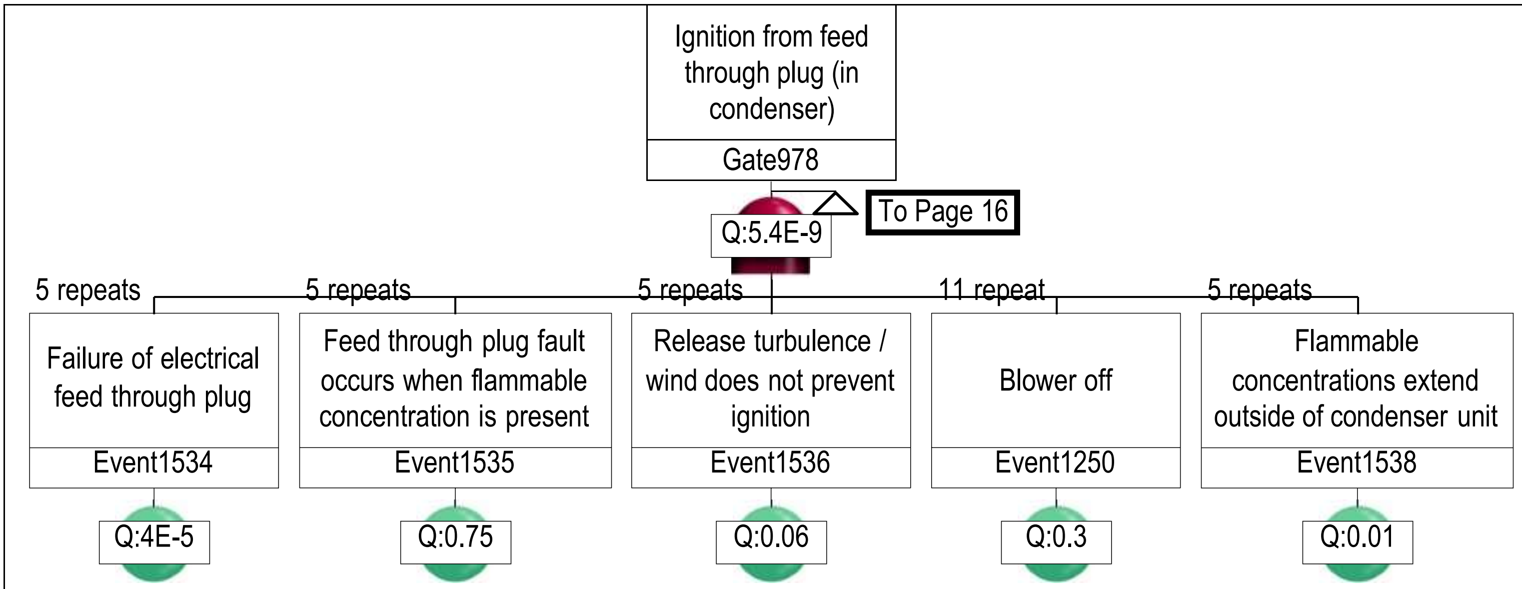
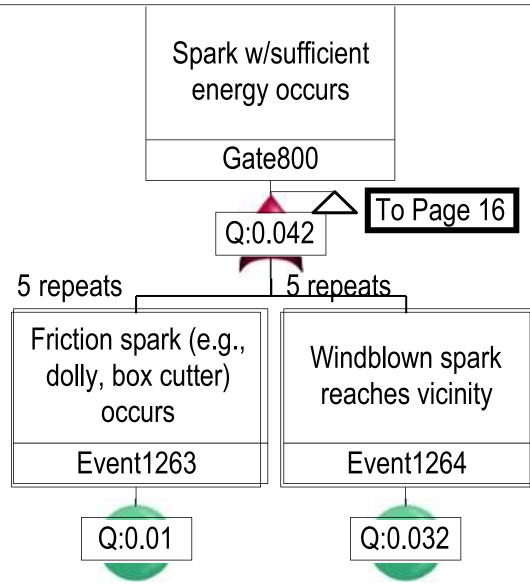

Ignition from feed through plug (in condenser)
Gate980
Q:5.4E-9
To Page 15
5 repeats
5 repeats
5 repeats
11 repeat
5 repeats
Failure of electrical feed through plug
Event1534
Q:4E-5
Feed through plug fault occurs when flammable concentration is present
Event1535
Q:0.75
Release turbulence / wind does not prevent ignition
Event1536
Q:0.06
Blower off
Event1250
Q:0.3
Flammable concentrations extend outside of condenser unit
Event1538
Q:0.01

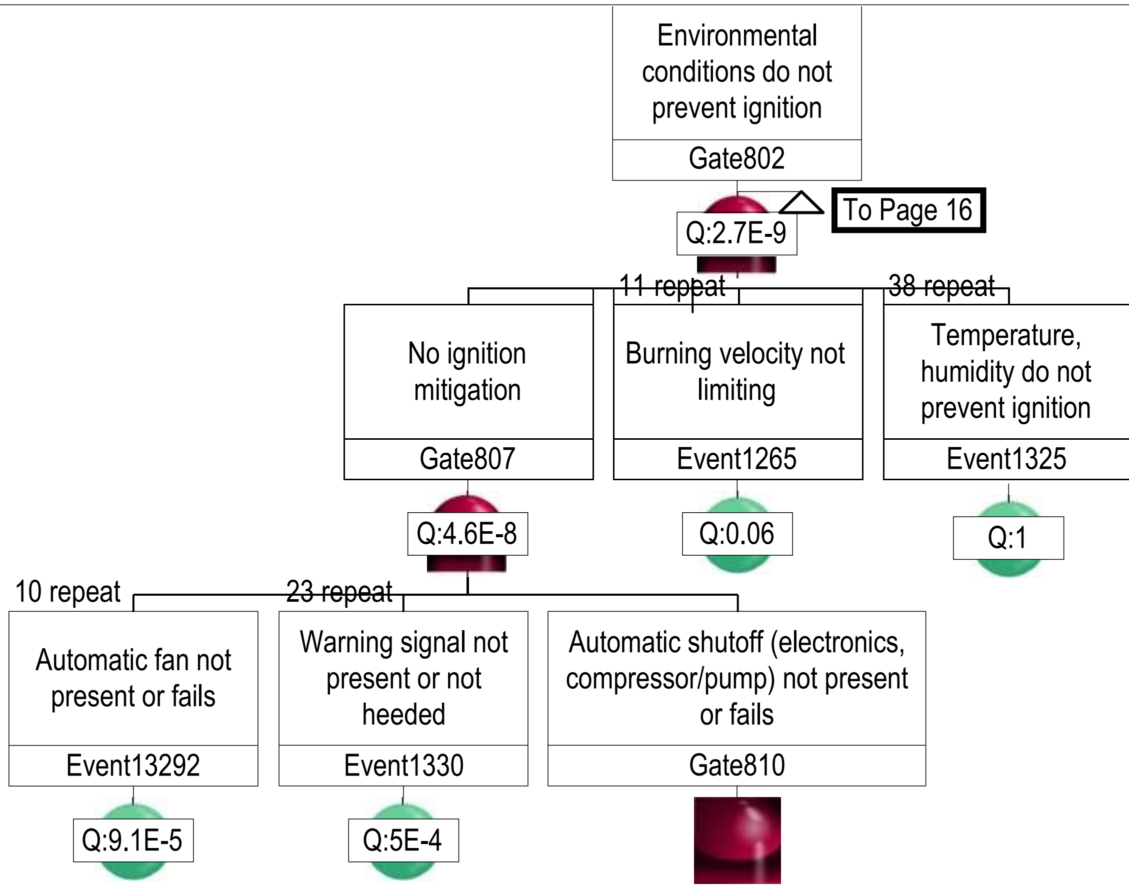
File Name: AHRI-3c-trailer.RFP

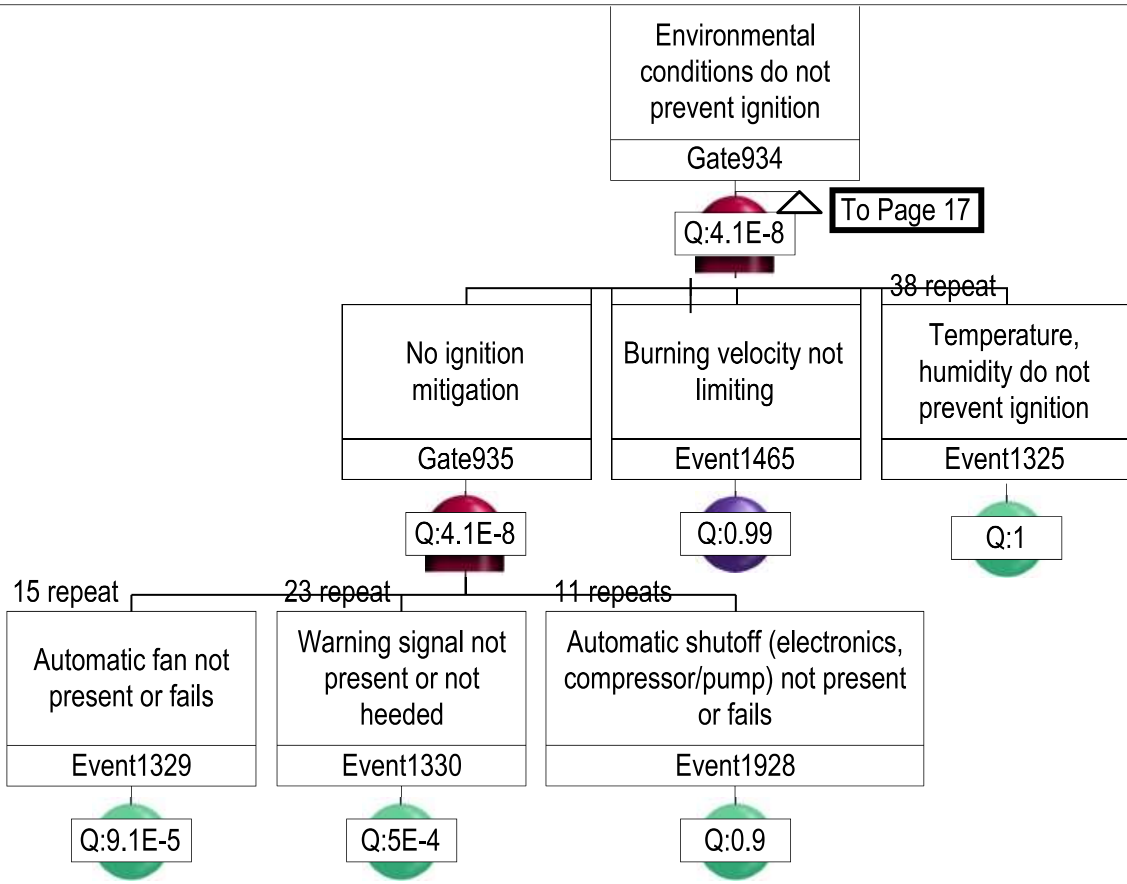


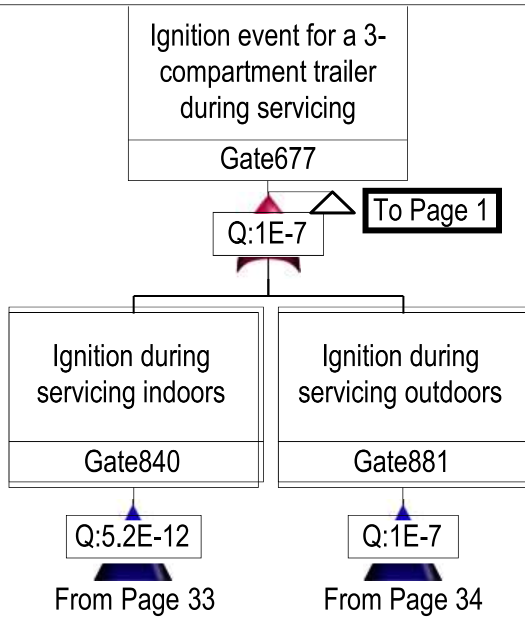
File Name: AHRI-3c-trailer.RFP



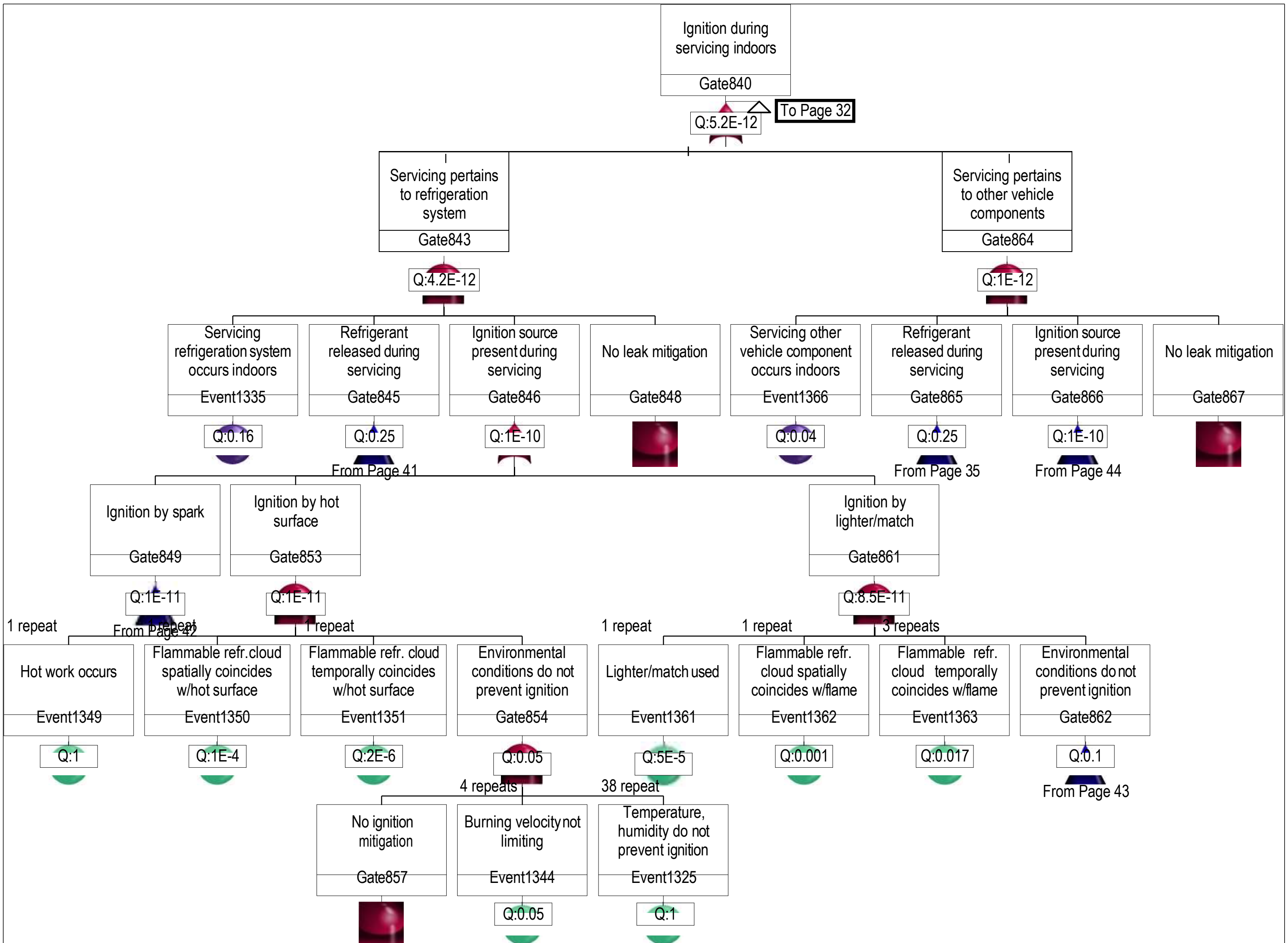

Spark w/sufficient energy occurs
Gate800
Q:0.042
To Page 16
5 repeats
5 repeats
Friction spark (e.g., dolly, box cutter) occurs
Event1263
Q:0.01
Windblown spark reaches vicinity
Event1264
Q:0.032

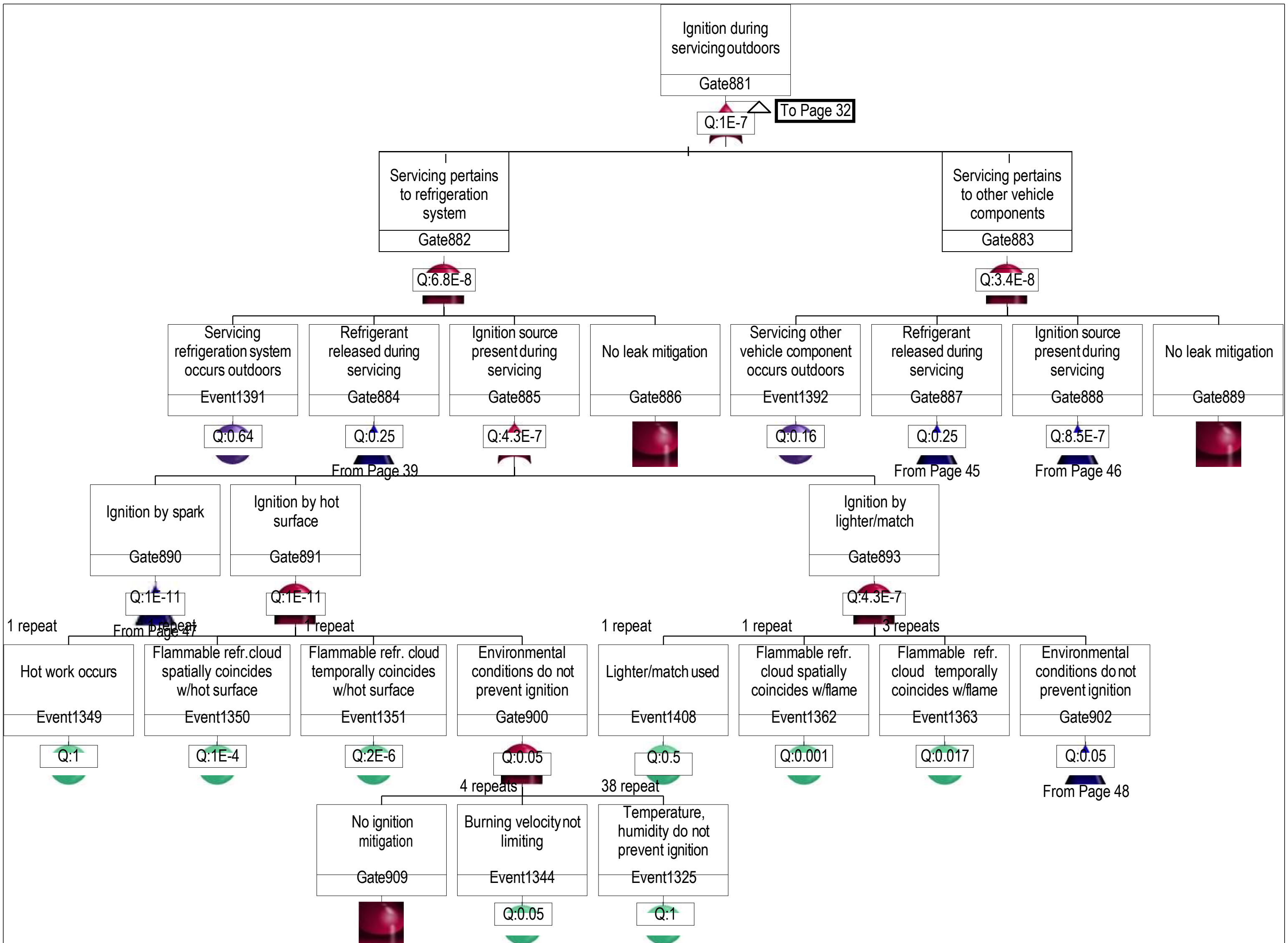

Environmental conditions do not prevent ignition
Gate802
Q:2.7E-9
To Page 16
11 repeat
38 repeat
No ignition mitigation
Gate807
Burning velocity not limiting
Event1265
Temperature, humidity do not prevent ignition
Event1325
Q:4.6E-8
Q:0.06
Q:1
10 repeat
23 repeat
Automatic fan not present or fails
Event13292
Warning signal not present or not heeded
Event1330
Automatic shutoff (electronics, compressor/pump) not present or fails
Gate810
Q:9.1E-5
Q:5E-4

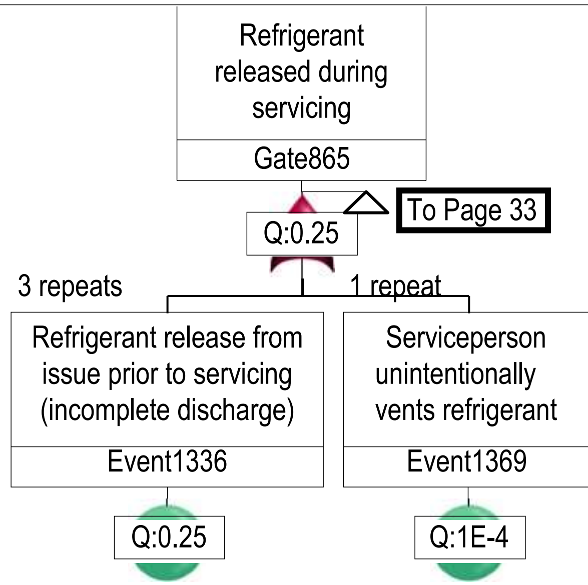

Environmental conditions do not prevent ignition
Gate934
To Page 17
Q:4.1E-8
No ignition mitigation
Gate935
Burning velocity not limiting
Event1465
38 repeat
Temperature, humidity do not prevent ignition
Event1325
Q:4.1E-8
Q:0.99
Q:1
15 repeat
23 repeat
11 repeats
Automatic fan not present or fails
Event1329
Warning signal not present or not heeded
Event1330
Automatic shutoff (electronics, compressor/pump) not present or fails
Event1928
Q:9.1E-5
Q:5E-4
Q:0.9


Ignition event for a 3-compartment trailer during servicing
Gate677
Q:1E-7
To Page 1
Ignition during servicing indoors
Gate840
Q:5.2E-12
From Page 33
Ignition during servicing outdoors
Gate881
Q:1E-7
From Page 34

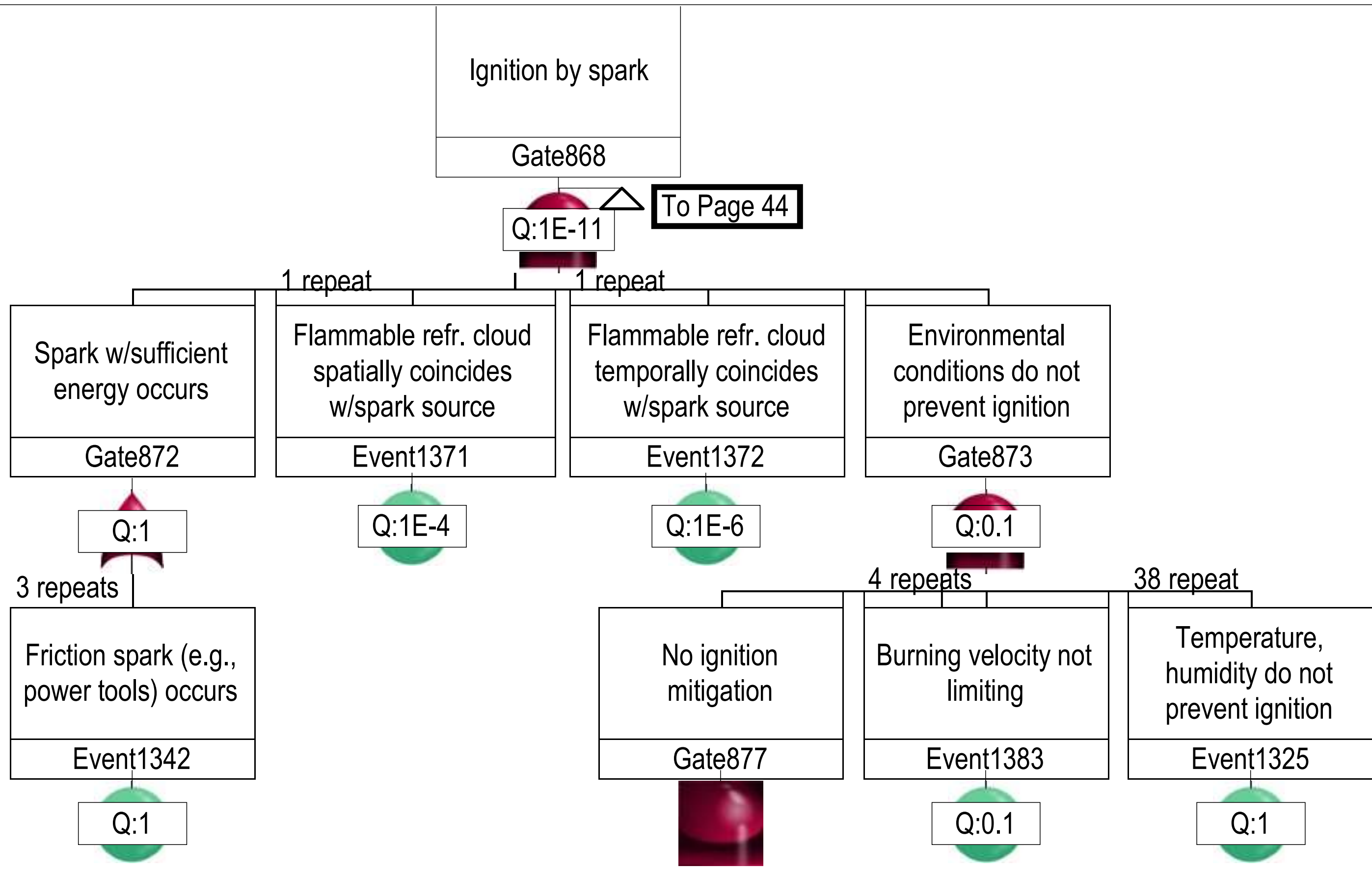
File Name: AHRI-3c-trailer.RFP

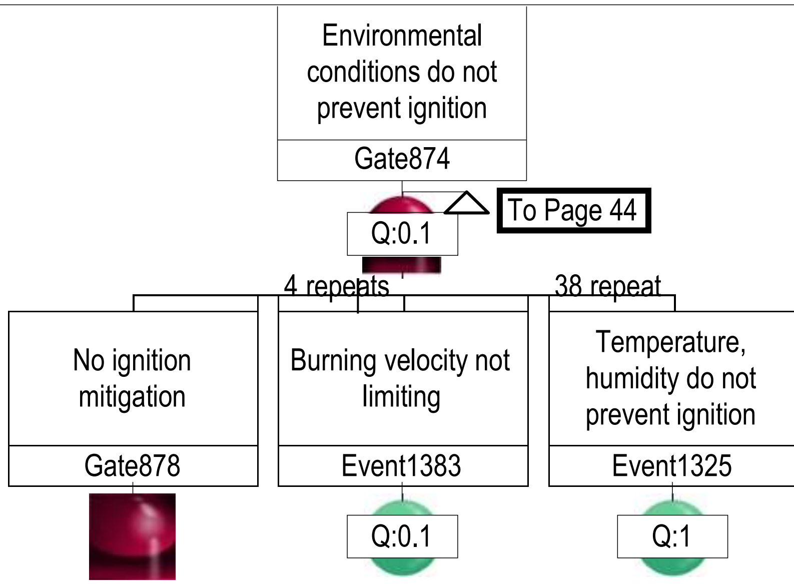


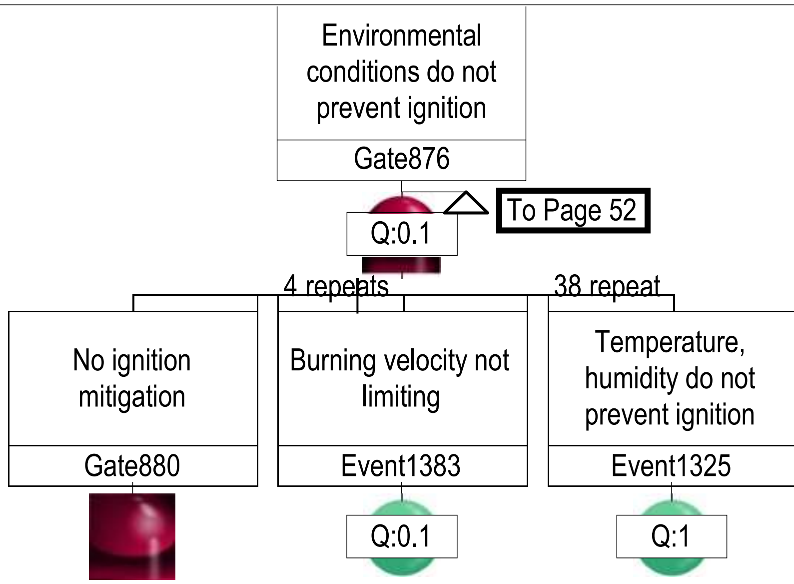

Ignition during servicing outdoors
Gate881
Q:1E-7
To Page 32
Servicing pertains to refrigeration system
Gate882
Q:6.8E-8
Servicing pertains to other vehicle components
Gate883
Q:3.4E-8
Servicing refrigeration system occurs outdoors
Event1391
Q:0.64
Refrigerant released during servicing
Gate884
Q:0.25
From Page 39
Ignition source present during servicing
Gate885
Q:4.3E-7
No leak mitigation
Gate886
Servicing other vehicle component occurs outdoors
Event1392
Q:0.16
Refrigerant released during servicing
Gate887
Q:0.25
From Page 45
Ignition source present during servicing
Gate888
Q:8.5E-7
From Page 46
No leak mitigation
Gate889
Ignition by spark
Gate890
Q:1E-11
From Page 47
Ignition by hot surface
Gate891
Q:1E-11
Ignition by lighter/match
Gate893
Q:4.3E-7
1 repeat
1 repeat
1 repeat
1 repeat
1 repeat
3 repeats
Hot work occurs
Event1349
Q:1
Flammable refr.cloud spatially coincides w/hot surface
Event1350
Q:1E-4
Flammable refr. cloud temporally coincides w/hot surface
Event1351
Q:2E-6
Environmental conditions do not prevent ignition
Gate900
Q:0.05
Lighter/match used
Event1408
Q:0.5
Flammable refr. cloud spatially coincides w/flame
Event1362
Q:0.001
Flammable refr. cloud temporally coincides w/flame
Event1363
Q:0.017
Environmental conditions do not prevent ignition
Gate902
Q:0.05
From Page 48
4 repeats
38 repeat
No ignition mitigation
Gate909
Burning velocity not limiting
Event1344
Q:0.05
Temperature, humidity do not prevent ignition
Event1325
Q:1

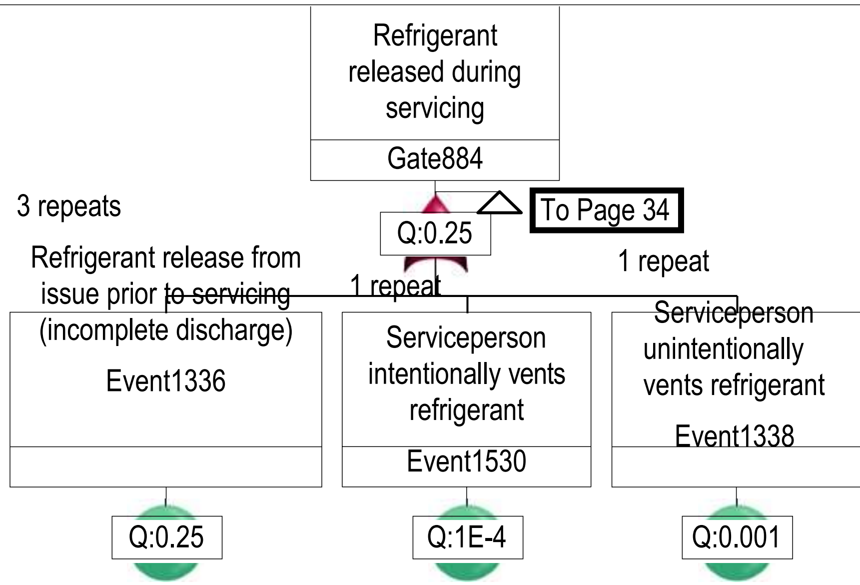

Refrigerant released during servicing
Gate865
Q:0.25
To Page 33
3 repeats
1 repeat
Refrigerant release from issue prior to servicing (incomplete discharge)
Event1336
Q:0.25
Serviceperson unintentionally vents refrigerant
Event1369
Q:1E-4

File Name: AHRI-3c-trailer.RFP

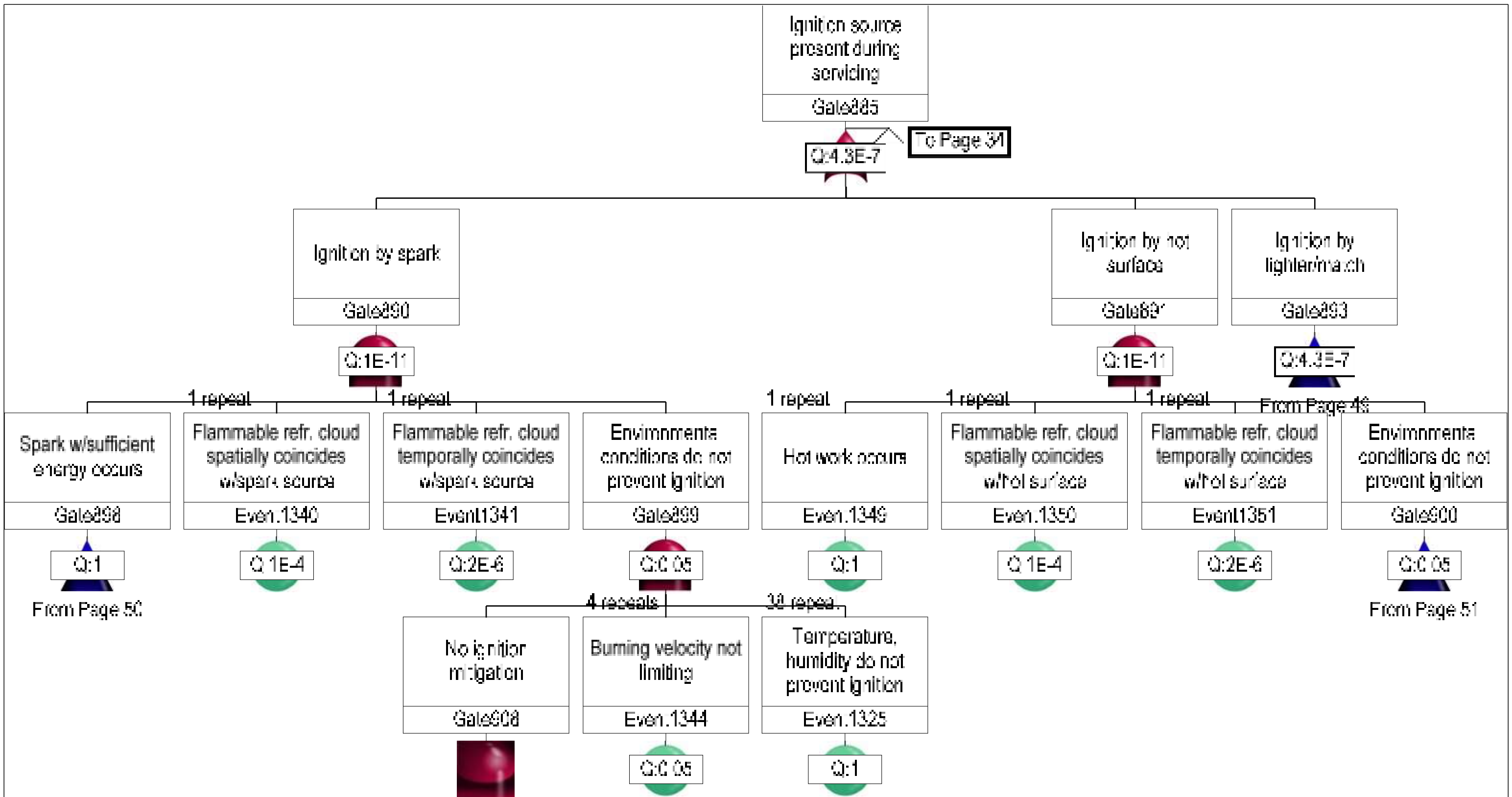


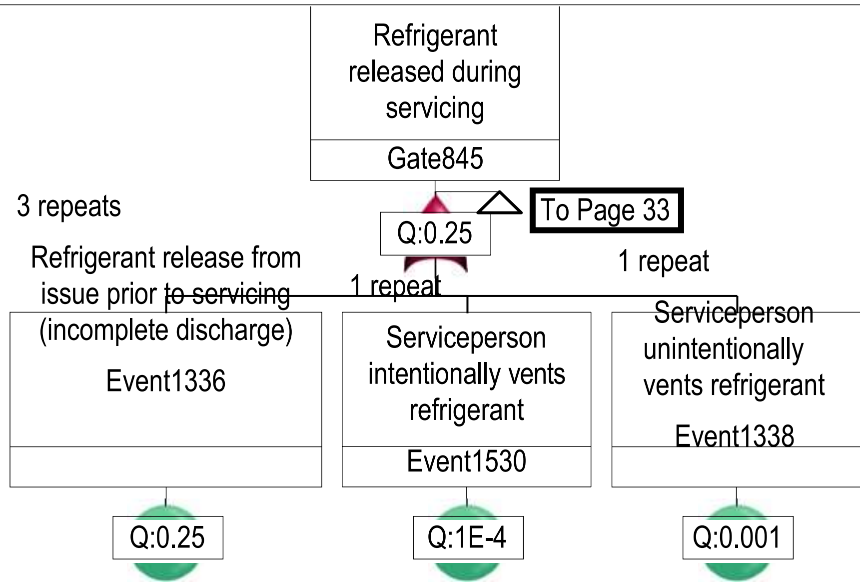

Environmental conditions do not prevent ignition
Gate874
Q:0.1
To Page 44
4 repeats
38 repeat
No ignition mitigation
Gate878
Burning velocity not limiting
Event1383
Q:0.1
Temperature, humidity do not prevent ignition
Event1325
Q:1

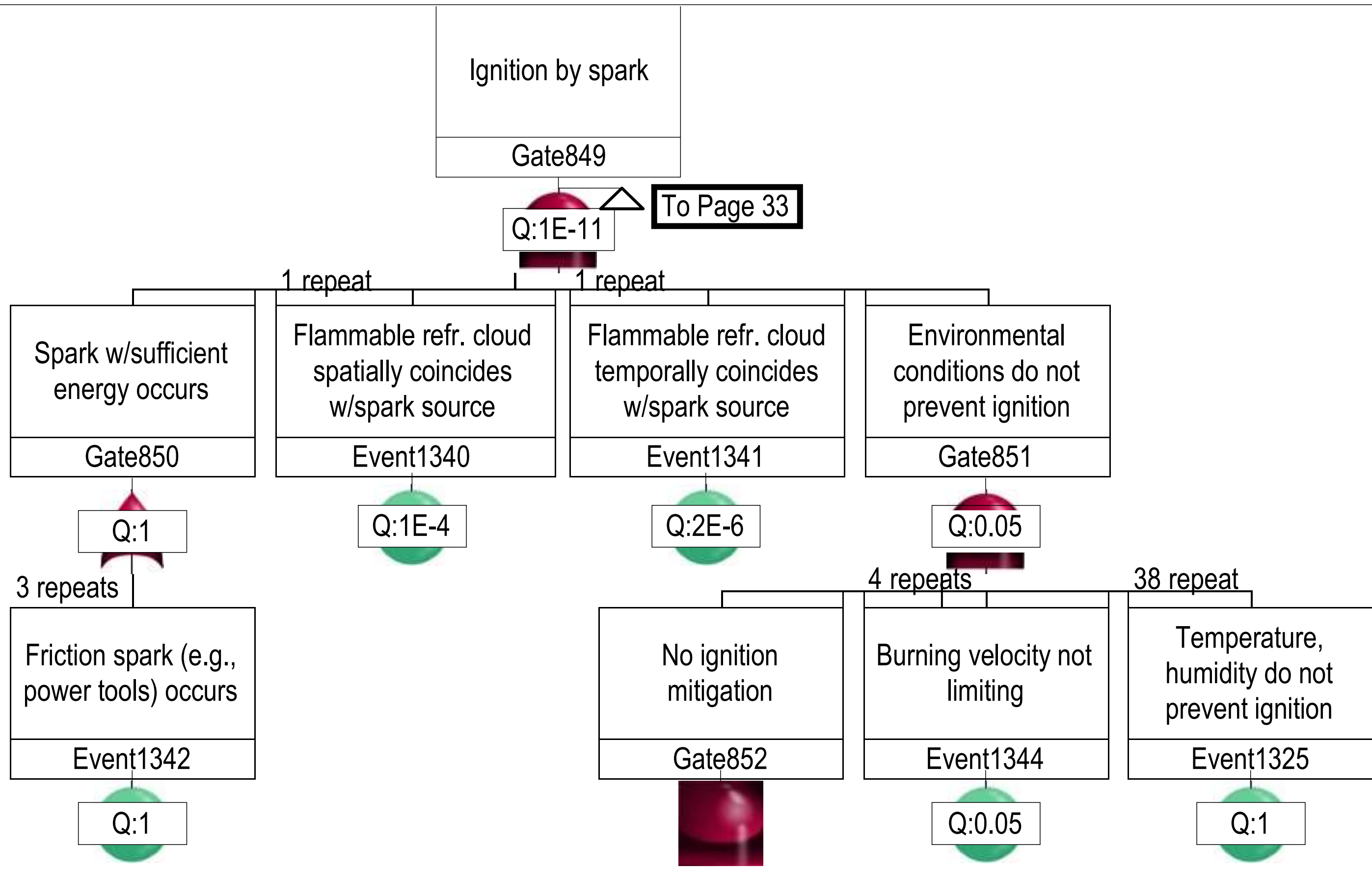

Environmental conditions do not prevent ignition
Gate876
Q:0.1
To Page 52
4 repeats
38 repeat
No ignition mitigation
Gate880
Burning velocity not limiting
Event1383
Q:0.1
Temperature, humidity do not prevent ignition
Event1325
Q:1

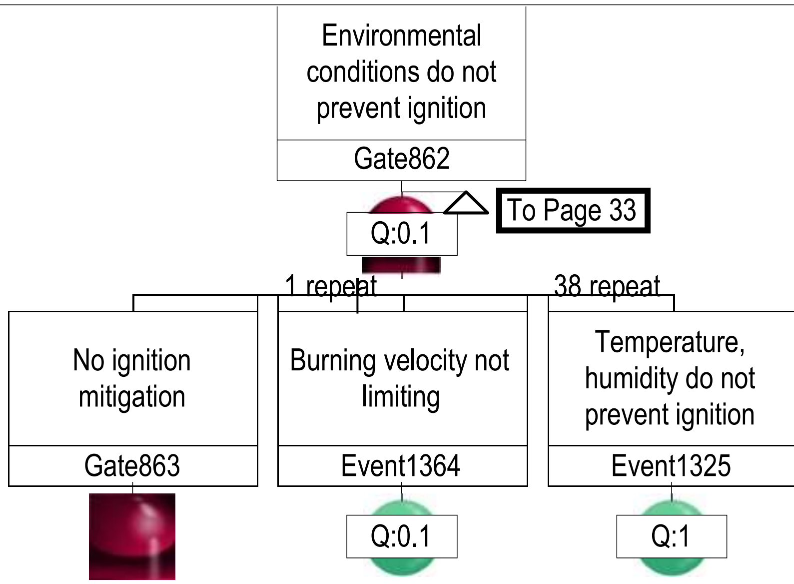

Refrigerant released during servicing
Gate884
Q:0.25
To Page 34
3 repeats
Refrigerant release from issue prior to servicing (incomplete discharge)
Event1336
Q:0.25
1 repeat
Serviceperson intentionally vents refrigerant
Event1530
Q:1E-4
1 repeat
Serviceperson unintentionally vents refrigerant
Event1338
Q:0.001

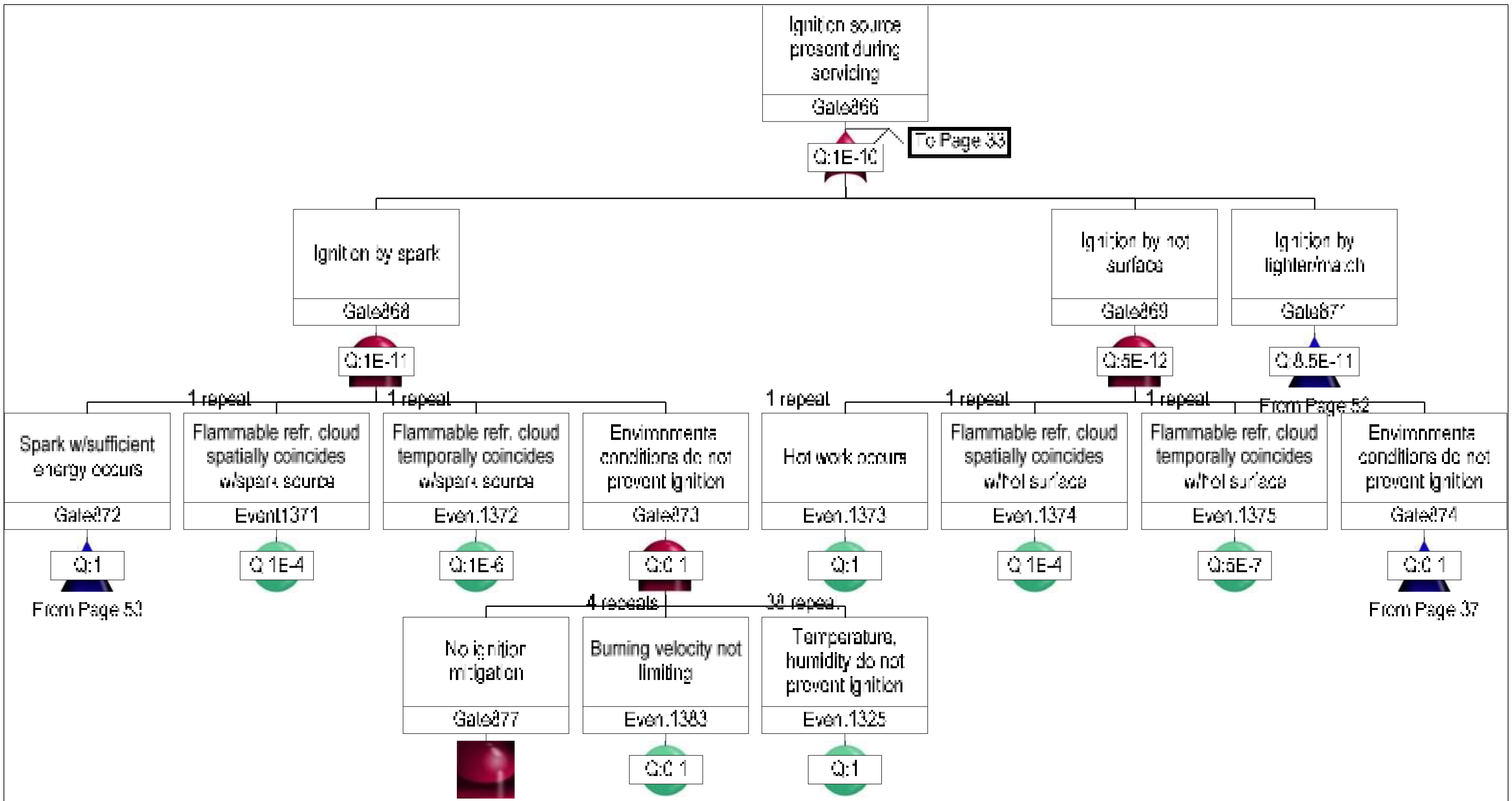
File Name: AHRI-3c-trailer.RFP

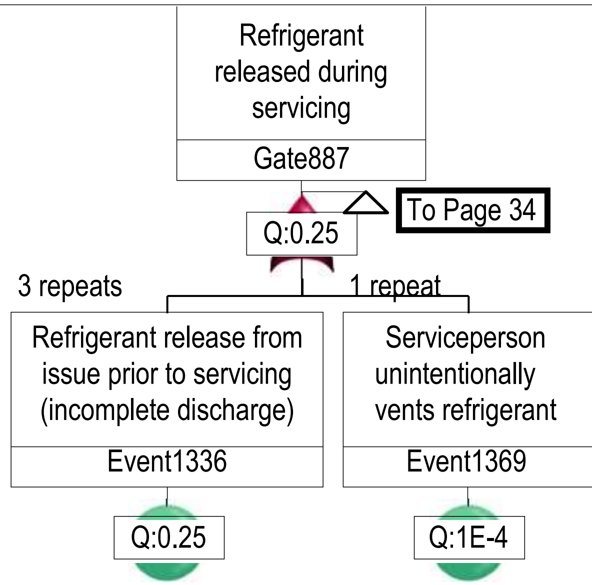



Refrigerant released during servicing
Gate845
3 repeats
Q:0.25
To Page 33
1 repeat
Refrigerant release from issue prior to servicing (incomplete discharge)
Event1336
1 repeat
Serviceperson intentionally vents refrigerant
Event1530
Serviceperson unintentionally vents refrigerant
Event1338
Q:0.25
Q:1E-4
Q:0.001

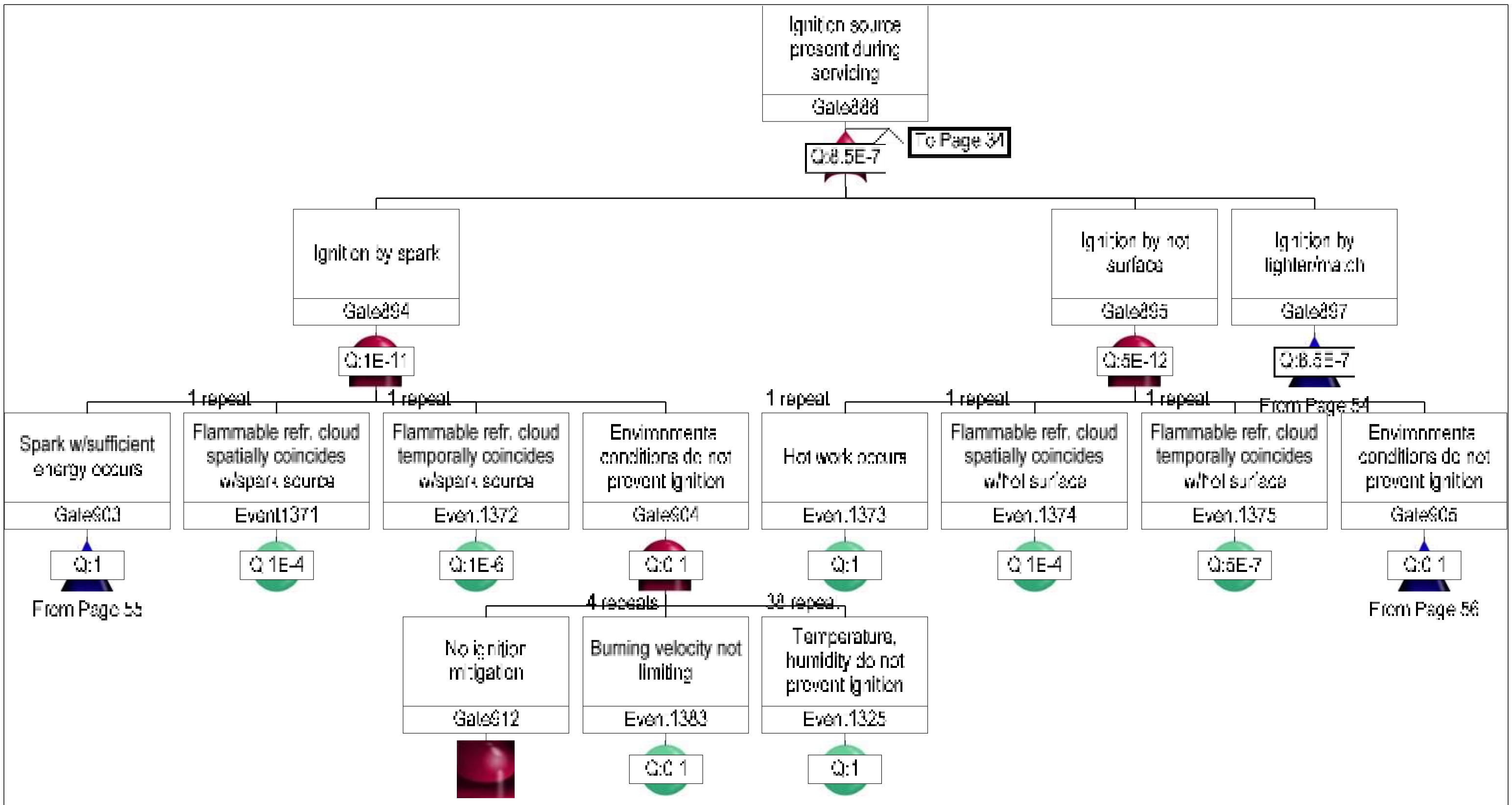

Ignition by spark
Gate849
Q:1E-11
To Page 33
1 repeat
1 repeat
Spark w/sufficient energy occurs
Gate850
Q:1
3 repeats
Flammable refr. cloud spatially coincides w/spark source
Event1340
Q:1E-4
Flammable refr. cloud temporally coincides w/spark source
Event1341
Q:2E-6
Environmental conditions do not prevent ignition
Gate851
Q:0.05
4 repeats
38 repeat
Friction spark (e.g., power tools) occurs
Event1342
Q:1
No ignition mitigation
Gate852
Burning velocity not limiting
Event1344
Q:0.05
Temperature, humidity do not prevent ignition
Event1325
Q:1

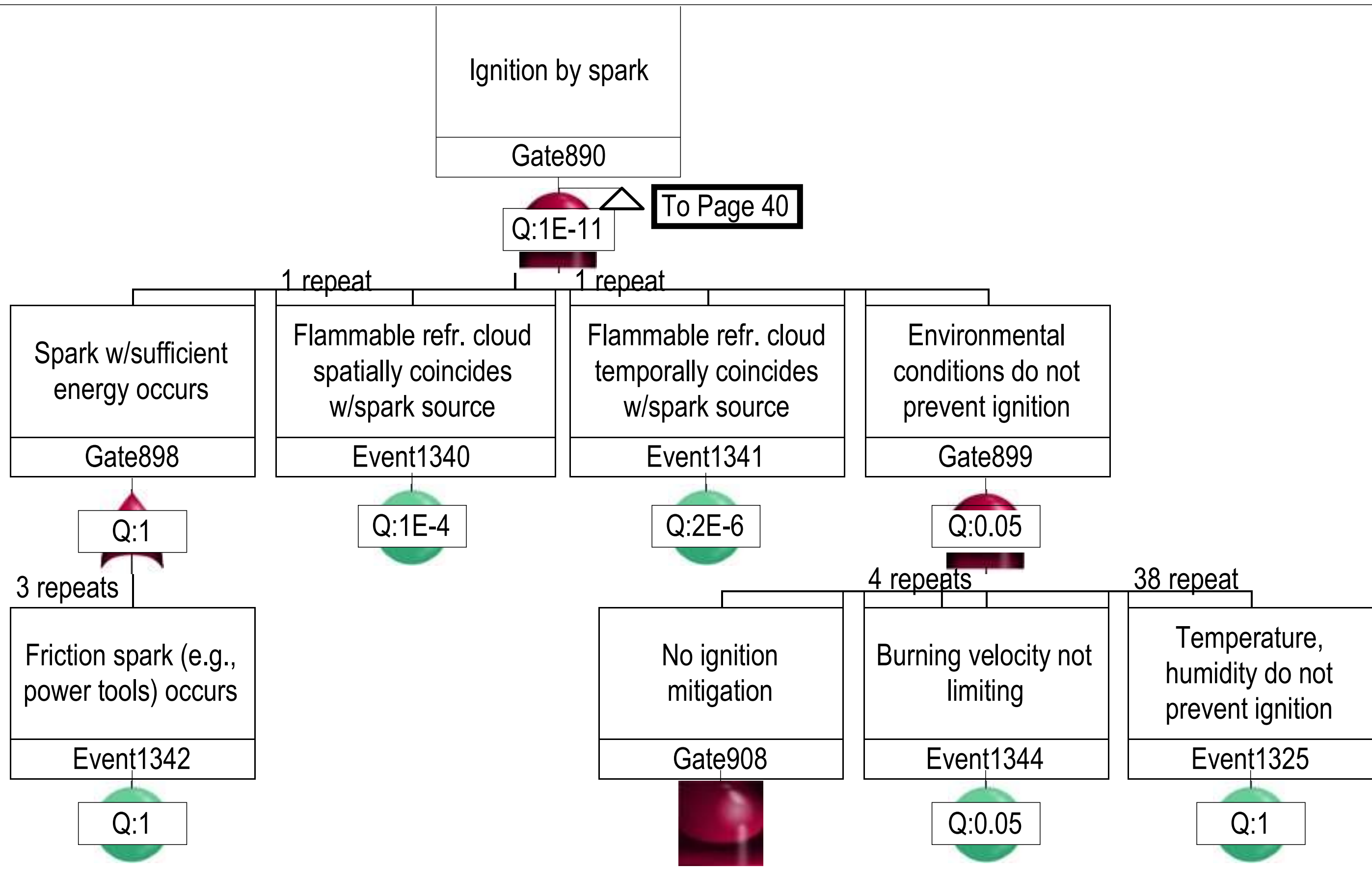

Environmental conditions do not prevent ignition
Gate862
Q:0.1
To Page 33
1 repeat
38 repeat
No ignition mitigation
Gate863
Burning velocity not limiting
Event1364
Q:0.1
Temperature, humidity do not prevent ignition
Event1325
Q:1

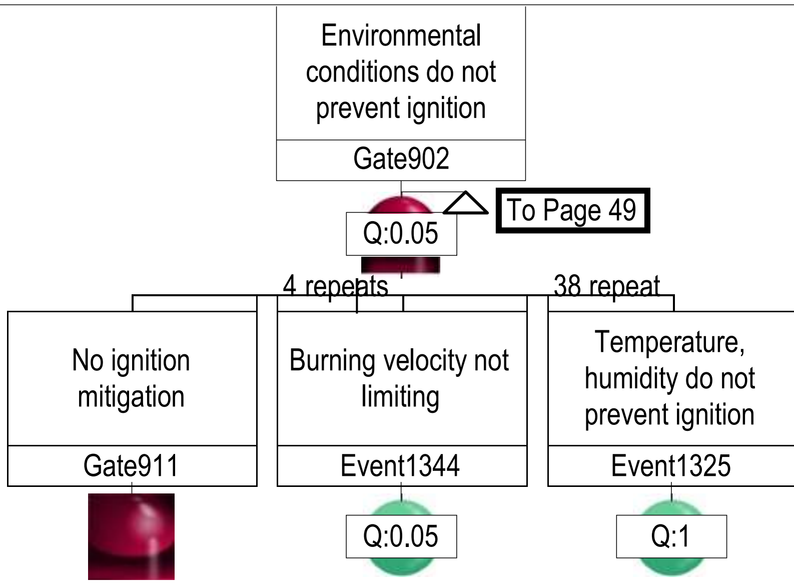

Ignition source present during servicing
Gate866
Q:1E-10
To Page 33
Ignition by spark
Gate868
Q:1E-11
Ignition by hot surface
Gate869
Q:5E-12
Ignition by lighter/match
Gate871
Q:8.5E-11
From Page 52
Spark w/sufficient energy occurs
Gate872
Q:1
From Page 53
1 repeat
Flammable refr. cloud spatially coincides w/spark source
Event1371
Q:1E-4
1 repeat
Flammable refr. cloud temporally coincides w/spark source
Event1372
Q:1E-6
Environmental conditions do not prevent ignition
Gate873
Q:0.1
1 repeat
Hot work occurs
Event1373
Q:1
1 repeat
Flammable refr. cloud spatially coincides w/hot surface
Event1374
Q:1E-4
1 repeat
Flammable refr. cloud temporally coincides w/hot surface
Event1375
Q:5E-7
Environmental conditions do not prevent ignition
Gate874
Q:0.1
From Page 37
4 repeats
38 repeats
No ignition mitigation
Gate877
Burning velocity not limiting
Event1383
Q:0.1
Temperature, humidity do not prevent ignition
Event1325
Q:1

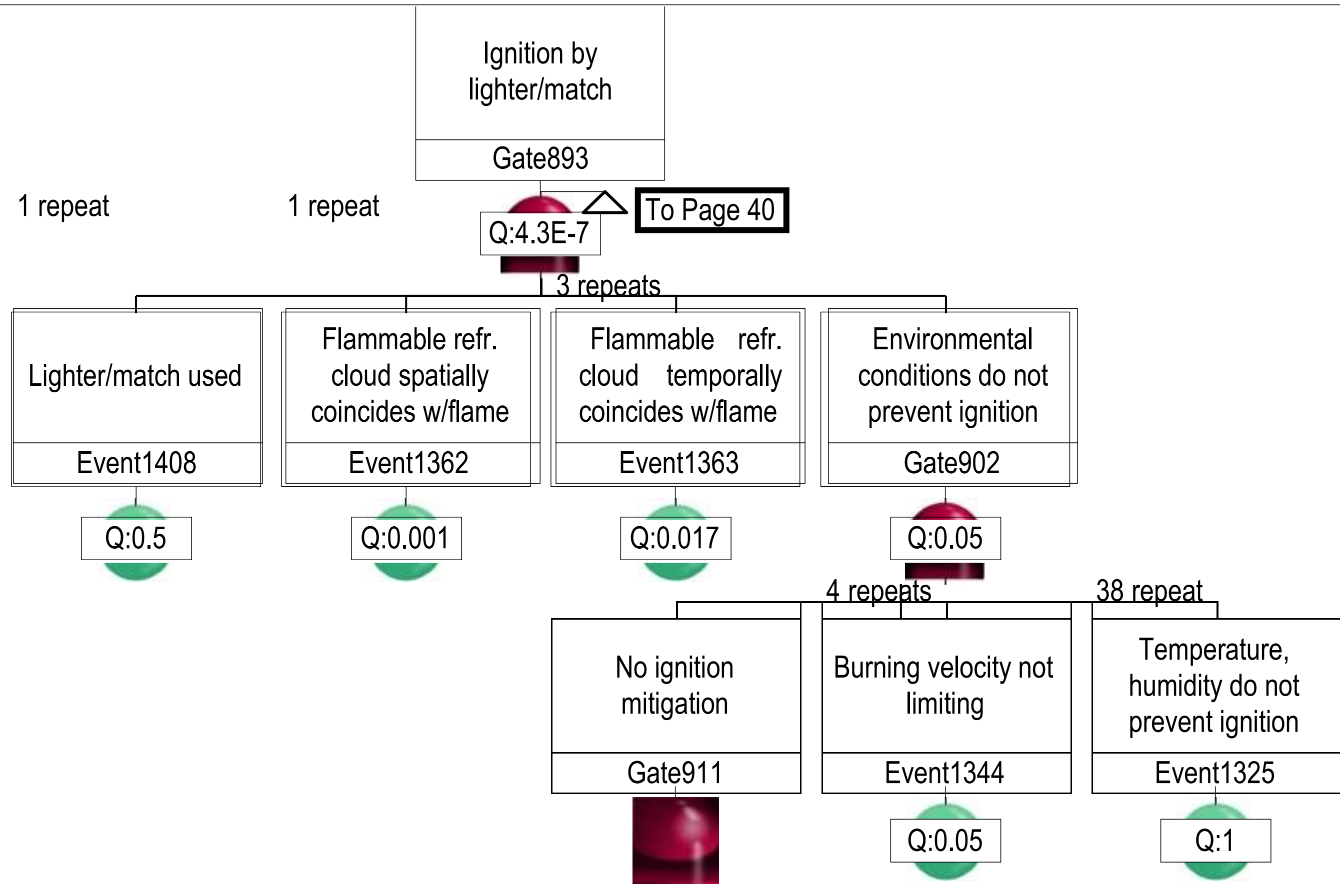

Refrigerant released during servicing
Gate887
Q:0.25
To Page 34
3 repeats
1 repeat
Refrigerant release from issue prior to servicing (incomplete discharge)
Event1336
Q:0.25
Serviceperson unintentionally vents refrigerant
Event1369
Q:1E-4

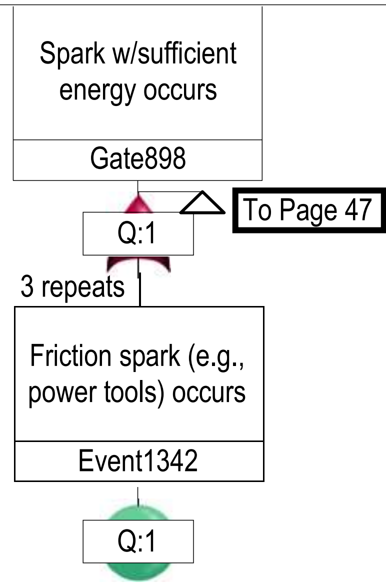
File Name: AHRI-3c-trailer.RFP

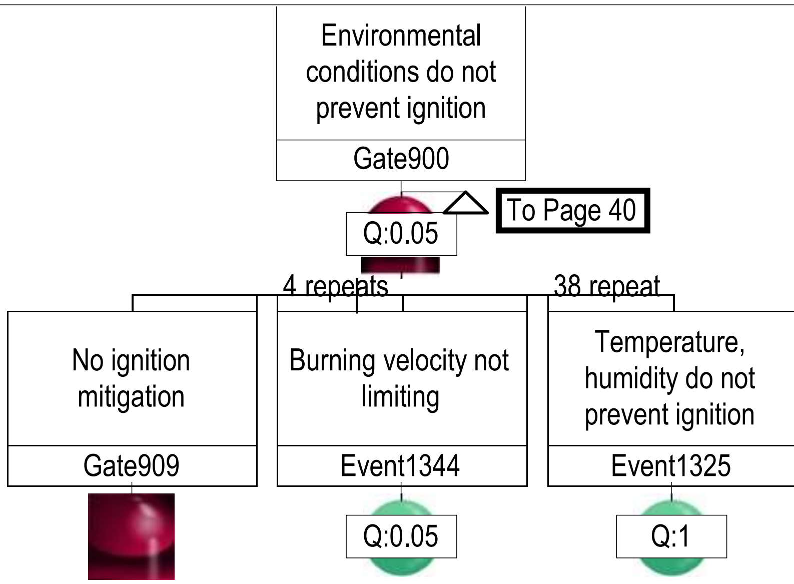


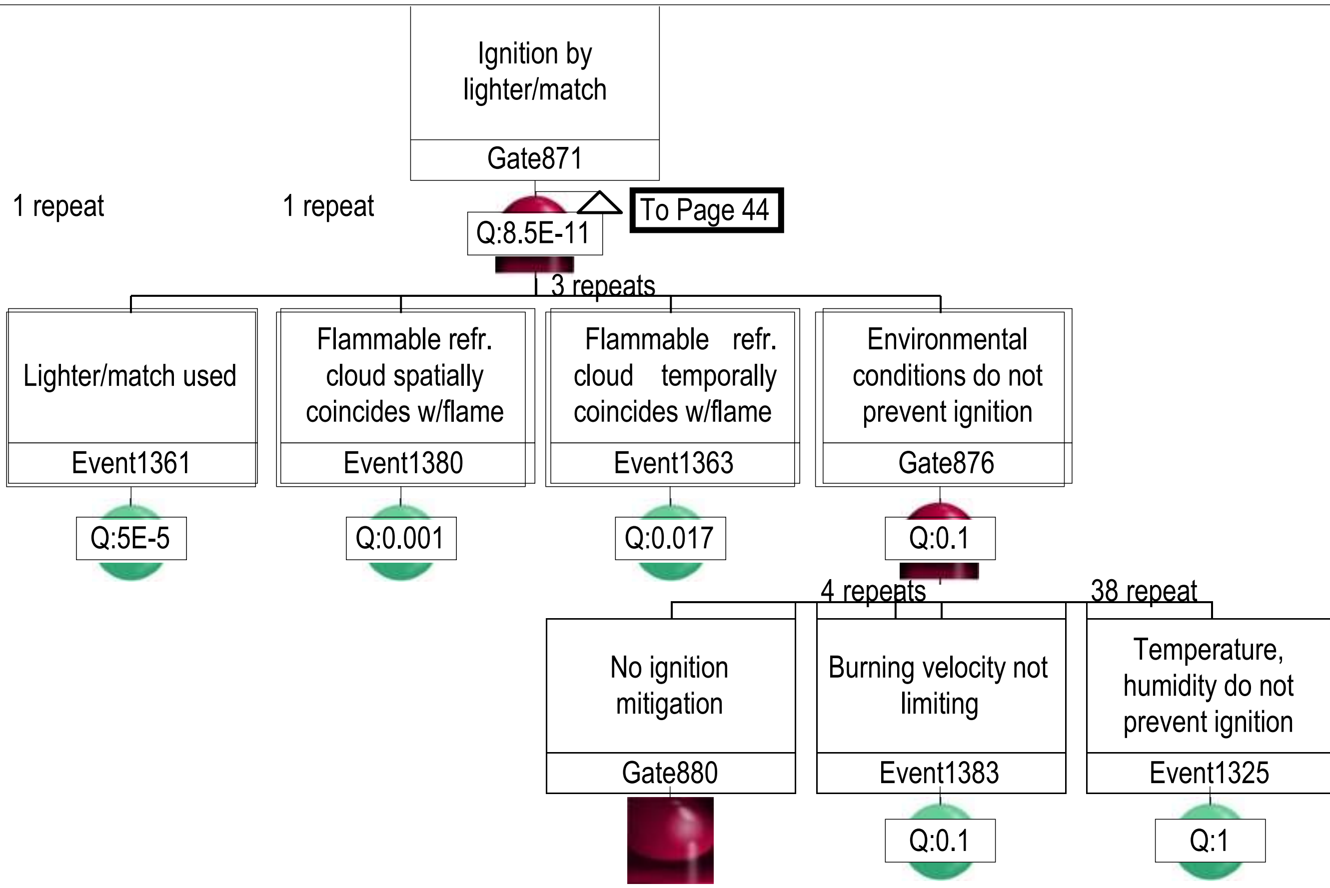

Ignition by spark
Gate890
Q:1E-11
To Page 40
1 repeat
1 repeat
Spark w/sufficient energy occurs
Gate898
Q:1
3 repeats
Flammable refr. cloud spatially coincides w/spark source
Event1340
Q:1E-4
Flammable refr. cloud temporally coincides w/spark source
Event1341
Q:2E-6
Environmental conditions do not prevent ignition
Gate899
Q:0.05
4 repeats
38 repeat
Friction spark (e.g., power tools) occurs
Event1342
Q:1
No ignition mitigation
Gate908
Burning velocity not limiting
Event1344
Q:0.05
Temperature, humidity do not prevent ignition
Event1325
Q:1

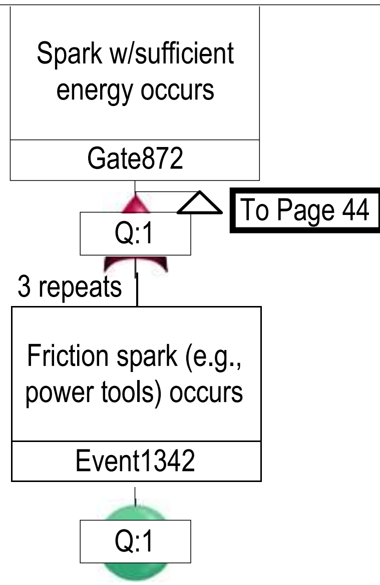

Environmental conditions do not prevent ignition
Gate902
Q:0.05
To Page 49
4 repeats
38 repeat
No ignition mitigation
Gate911
Burning velocity not limiting
Event1344
Q:0.05
Temperature, humidity do not prevent ignition
Event1325
Q:1

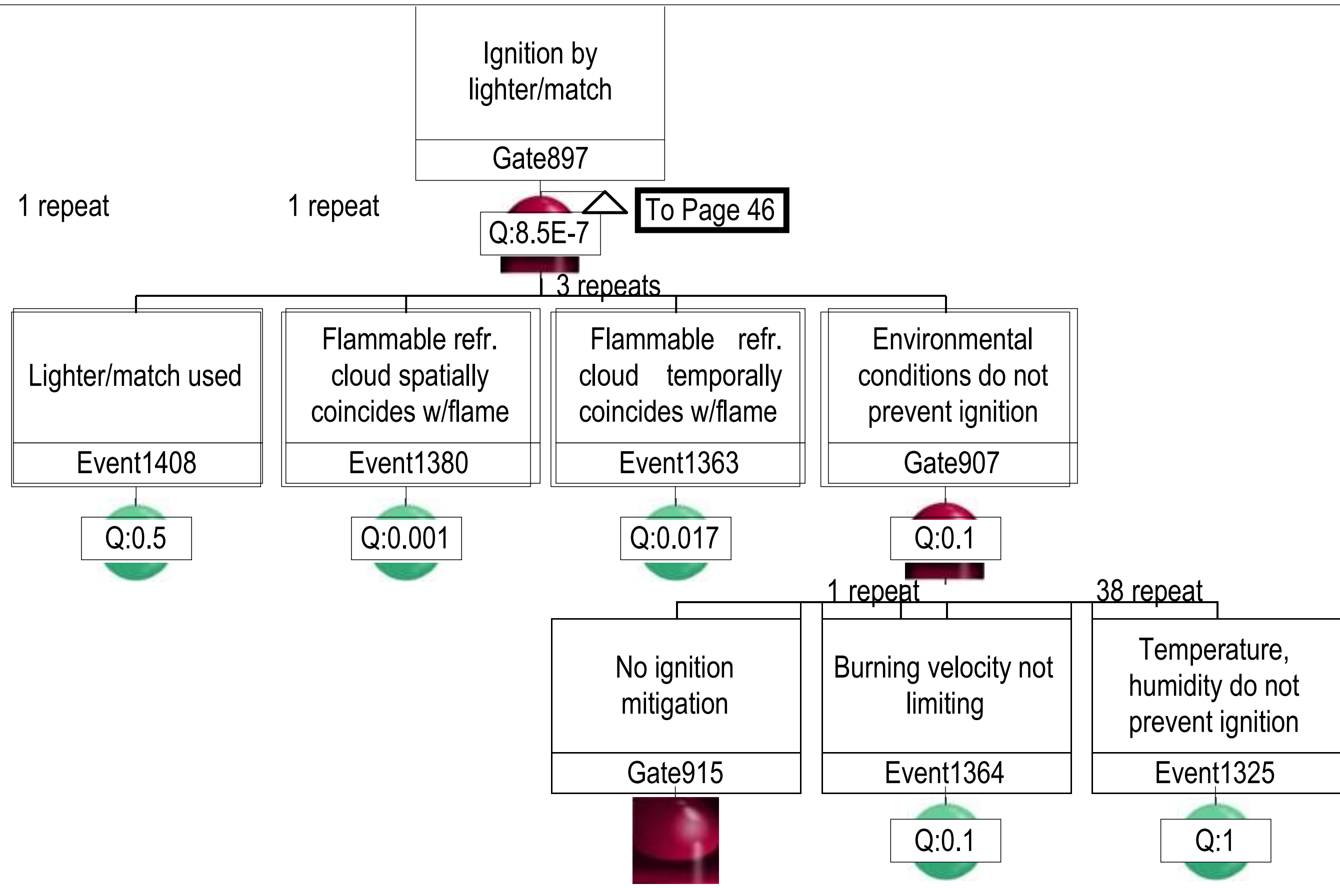

Ignition by lighter/match
Gate893
1 repeat
1 repeat
Q:4.3E-7
To Page 40
3 repeats
Lighter/match used
Event1408
Q:0.5
Flammable refr. cloud spatially coincides w/flame
Event1362
Q:0.001
Flammable refr. cloud temporally coincides w/flame
Event1363
Q:0.017
Environmental conditions do not prevent ignition
Gate902
Q:0.05
4 repeats
38 repeat
No ignition mitigation
Gate911
Burning velocity not limiting
Event1344
Q:0.05
Temperature, humidity do not prevent ignition
Event1325
Q:1

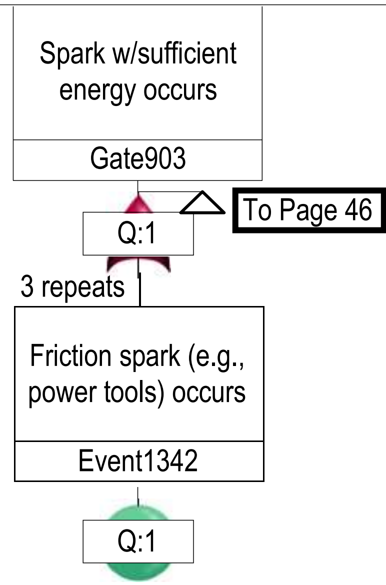

Spark w/sufficient energy occurs
Gate898
Q:1
To Page 47
3 repeats
Friction spark (e.g., power tools) occurs
Event1342
Q:1


Environmental conditions do not prevent ignition
Gate900
To Page 40
Q:0.05
4 repeats
38 repeat
No ignition mitigation
Gate909
Burning velocity not limiting
Event1344
Q:0.05
Temperature, humidity do not prevent ignition
Event1325
Q:1


Ignition by lighter/match
Gate871
1 repeat
1 repeat
Q:8.5E-11
To Page 44
3 repeats
Lighter/match used
Event1361
Q:5E-5
Flammable refr. cloud spatially coincides w/flame
Event1380
Q:0.001
Flammable refr. cloud temporally coincides w/flame
Event1363
Q:0.017
Environmental conditions do not prevent ignition
Gate876
Q:0.1
4 repeats
38 repeat
No ignition mitigation
Gate880
Burning velocity not limiting
Event1383
Q:0.1
Temperature, humidity do not prevent ignition
Event1325
Q:1


Spark w/sufficient energy occurs
Gate872
Q:1
To Page 44
3 repeats
Friction spark (e.g., power tools) occurs
Event1342
Q:1


Ignition by lighter/match
Gate897
Q:8.5E-7
To Page 46
1 repeat
1 repeat
3 repeats
Lighter/match used
Event1408
Q:0.5
Flammable refr. cloud spatially coincides w/flame
Event1380
Q:0.001
Flammable refr. cloud temporally coincides w/flame
Event1363
Q:0.017
Environmental conditions do not prevent ignition
Gate907
Q:0.1
1 repeat
38 repeat
No ignition mitigation
Gate915
Burning velocity not limiting
Event1364
Q:0.1
Temperature, humidity do not prevent ignition
Event1325
Q:1


Spark w/sufficient energy occurs
Gate903
Q:1
To Page 46
3 repeats
Friction spark (e.g., power tools) occurs
Event1342
Q:1

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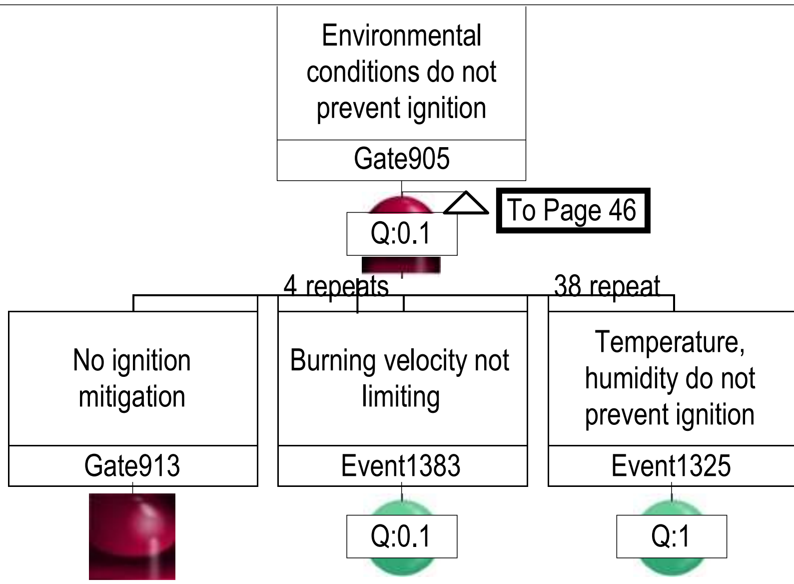
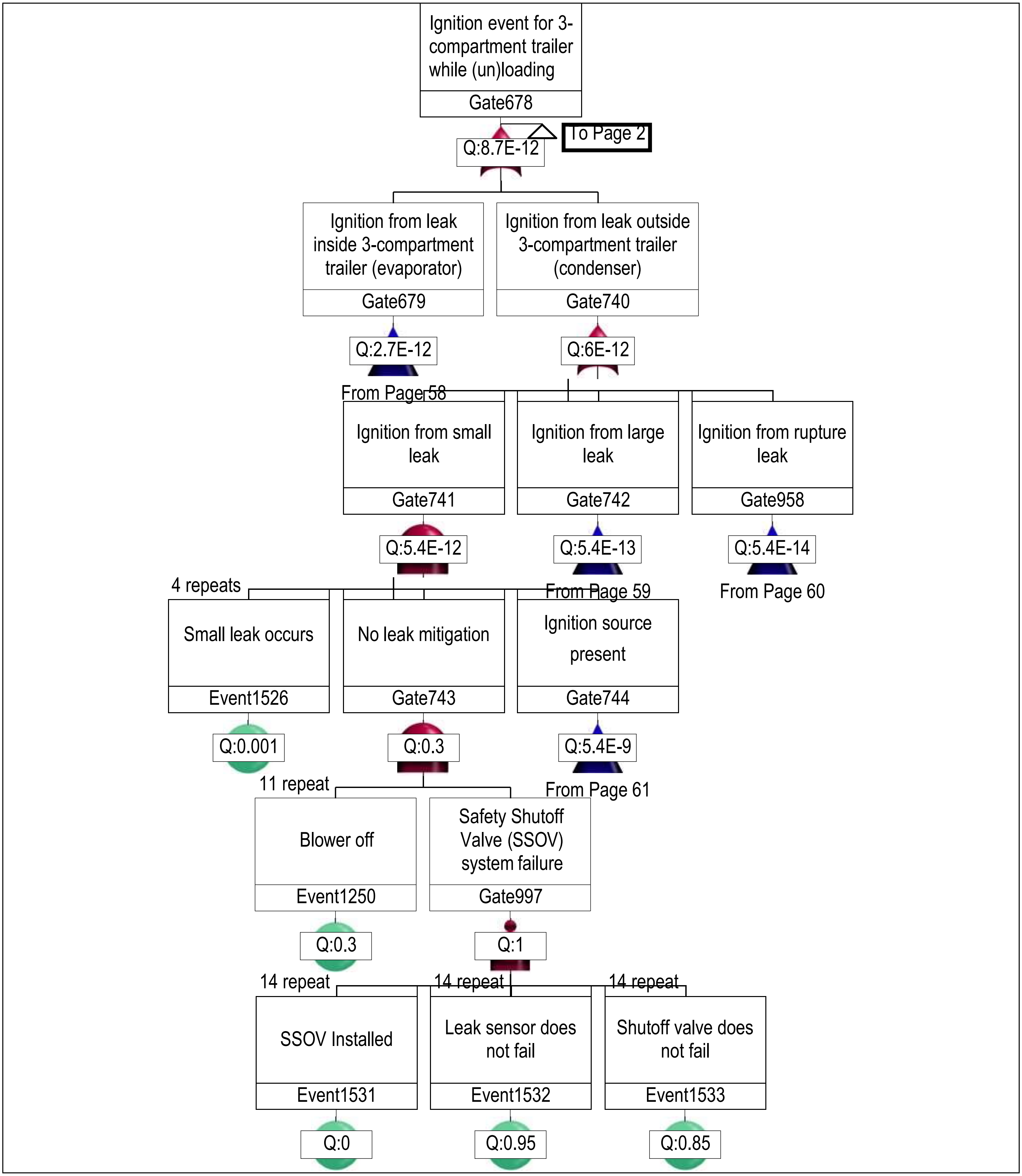
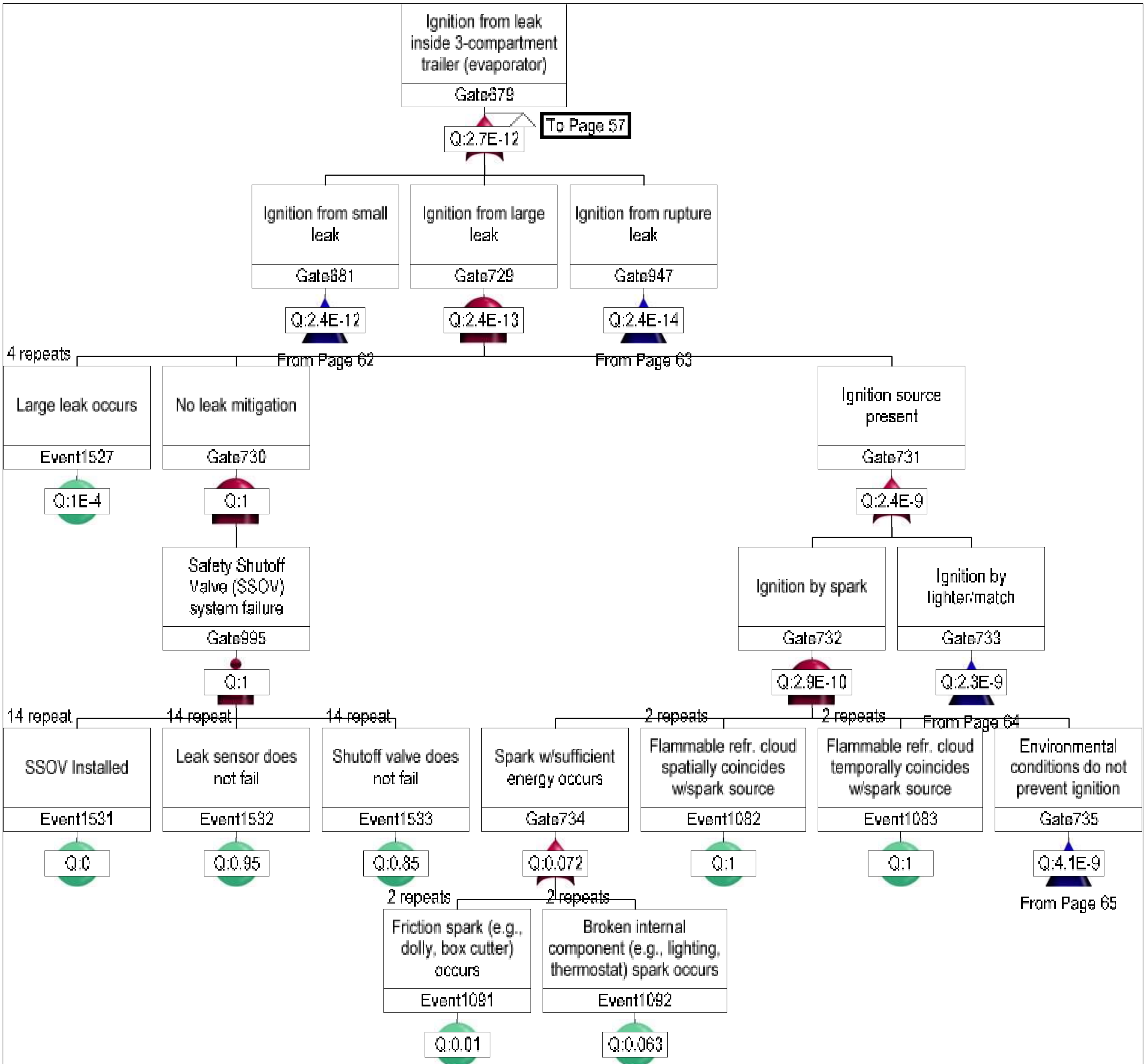



Ignition event for 3-compartment trailer while (un)loading
Gate678
Q:8.7E-12
To Page 2
Ignition from leak inside 3-compartment trailer (evaporator)
Gate679
Q:2.7E-12
From Page 58
Ignition from leak outside 3-compartment trailer (condenser)
Gate740
Q:6E-12
Ignition from small leak
Gate741
Q:5.4E-12
Ignition from large leak
Gate742
Q:5.4E-13
From Page 59
Ignition from rupture leak
Gate958
Q:5.4E-14
From Page 60
4 repeats
Small leak occurs
Event1526
Q:0.001
No leak mitigation
Gate743
Q:0.3
Ignition source present
Gate744
Q:5.4E-9
From Page 61
11 repeat
Blower off
Event1250
Q:0.3
Safety Shutoff Valve (SSOV) system failure
Gate997
Q:1
14 repeat
SSOV Installed
Event1531
Q:0
14 repeat
Leak sensor does not fail
Event1532
Q:0.95
14 repeat
Shutoff valve does not fail
Event1533
Q:0.85

File Name: AHRI-3c-trailer.RFP



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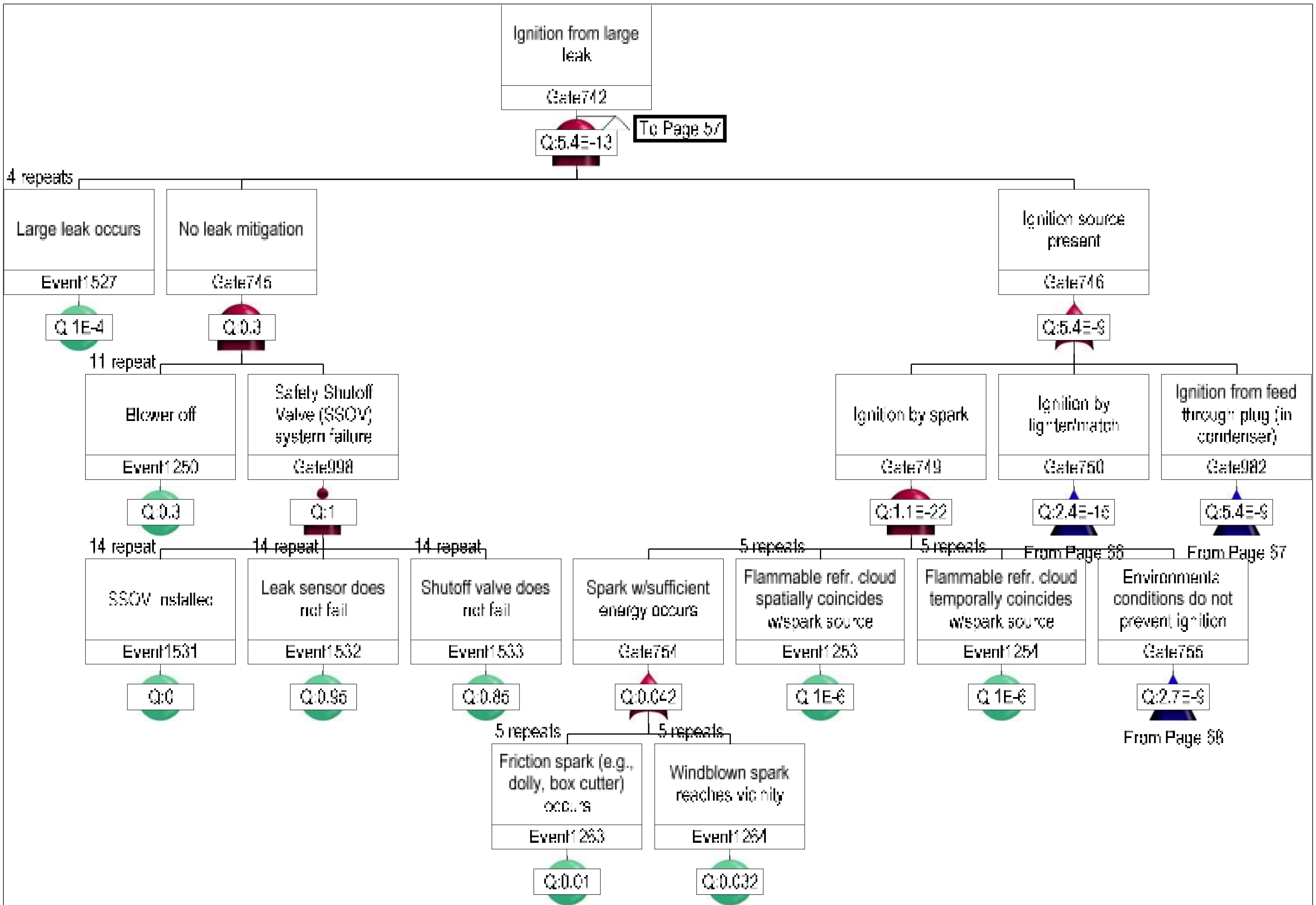
Ignition from large leak
Gate742
Q:5.4E-13
To Page 57
4 repeats
Large leak occurs
Event1527
Q:1E-4
No leak mitigation
Gate745
Q:0.3
Ignition source present
Gate746
Q:5.4E-9
11 repeat
Blower off
Event1250
Q:0.3
Safety Shutoff Valve (SSOV) system failure
Gate998
Q:1
Ignition by spark
Gate749
Q:1.1E-22
Ignition by lighter/match
Gate750
Q:2.4E-16
From Page 56
Ignition from feed through plug (in condenser)
Gate982
Q:5.4E-9
From Page 57
14 repeat
SSOV installed
Event1531
Q:0
14 repeat
Leak sensor does not fail
Event1532
Q:0.96
14 repeat
Shutoff valve does not fail
Event1533
Q:0.86
Spark w/sufficient energy occurs
Gate754
Q:0.042
5 repeats
Flammable refr. cloud spatially coincides w/spark source
Event1253
Q:1E-6
5 repeats
Flammable refr. cloud temporally coincides w/spark source
Event1254
Q:1E-6
Environmental conditions do not prevent ignition
Gate755
Q:2.7E-9
From Page 58
5 repeats
Friction spark (e.g., dolly, box cutter) occurs
Event1263
Q:0.01
5 repeats
Windblown spark reaches vicinity
Event1264
Q:0.032

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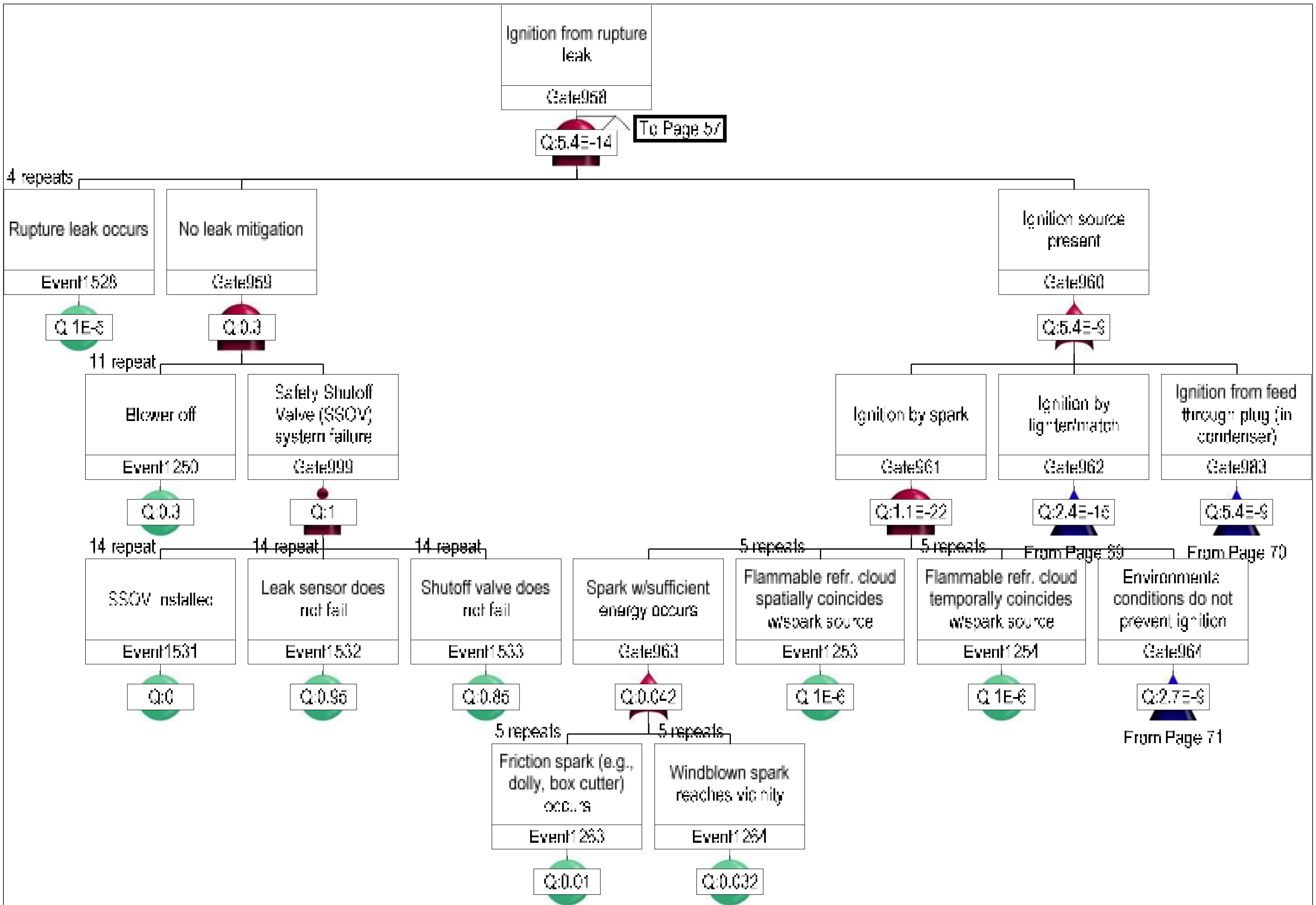
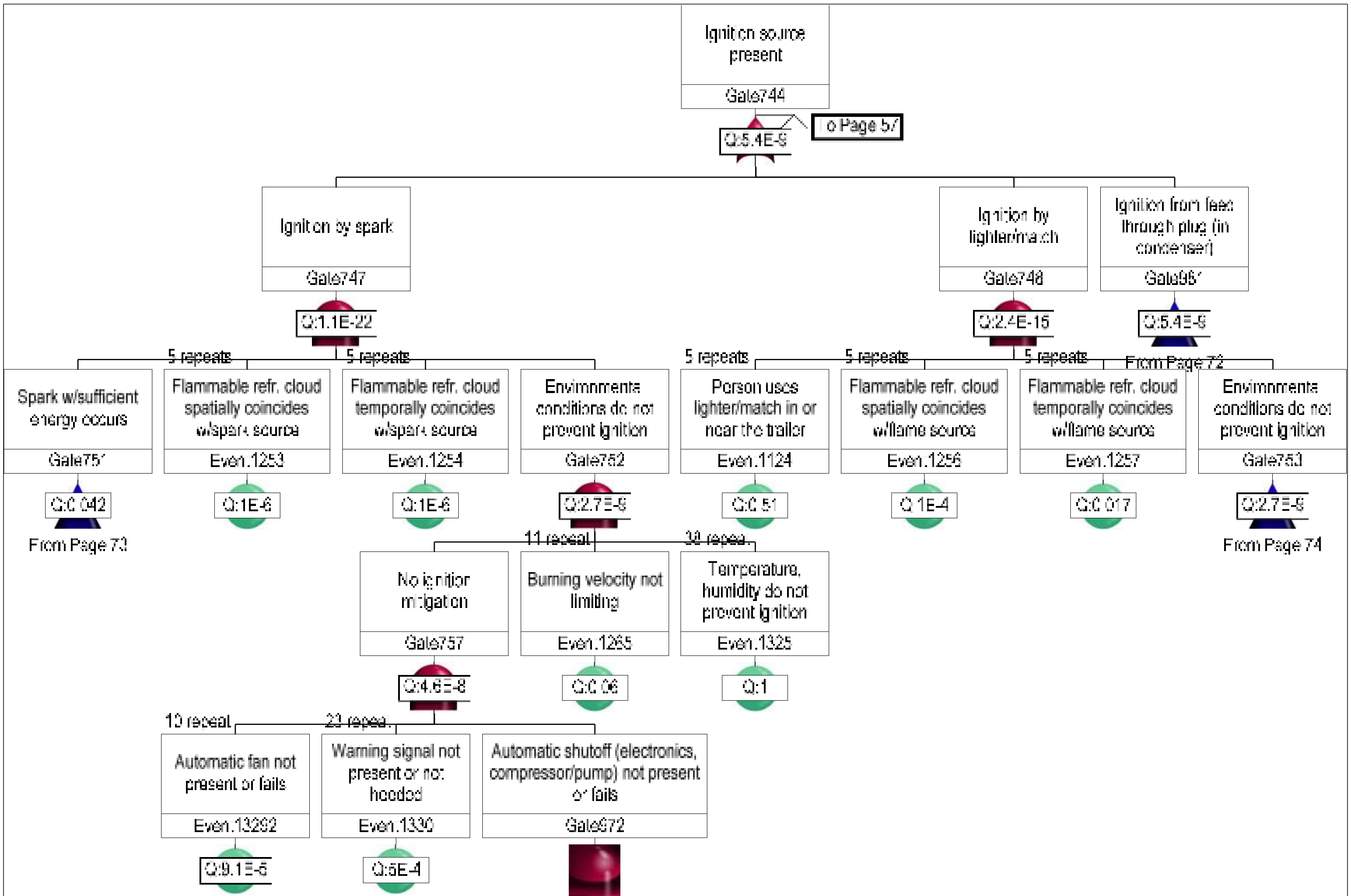
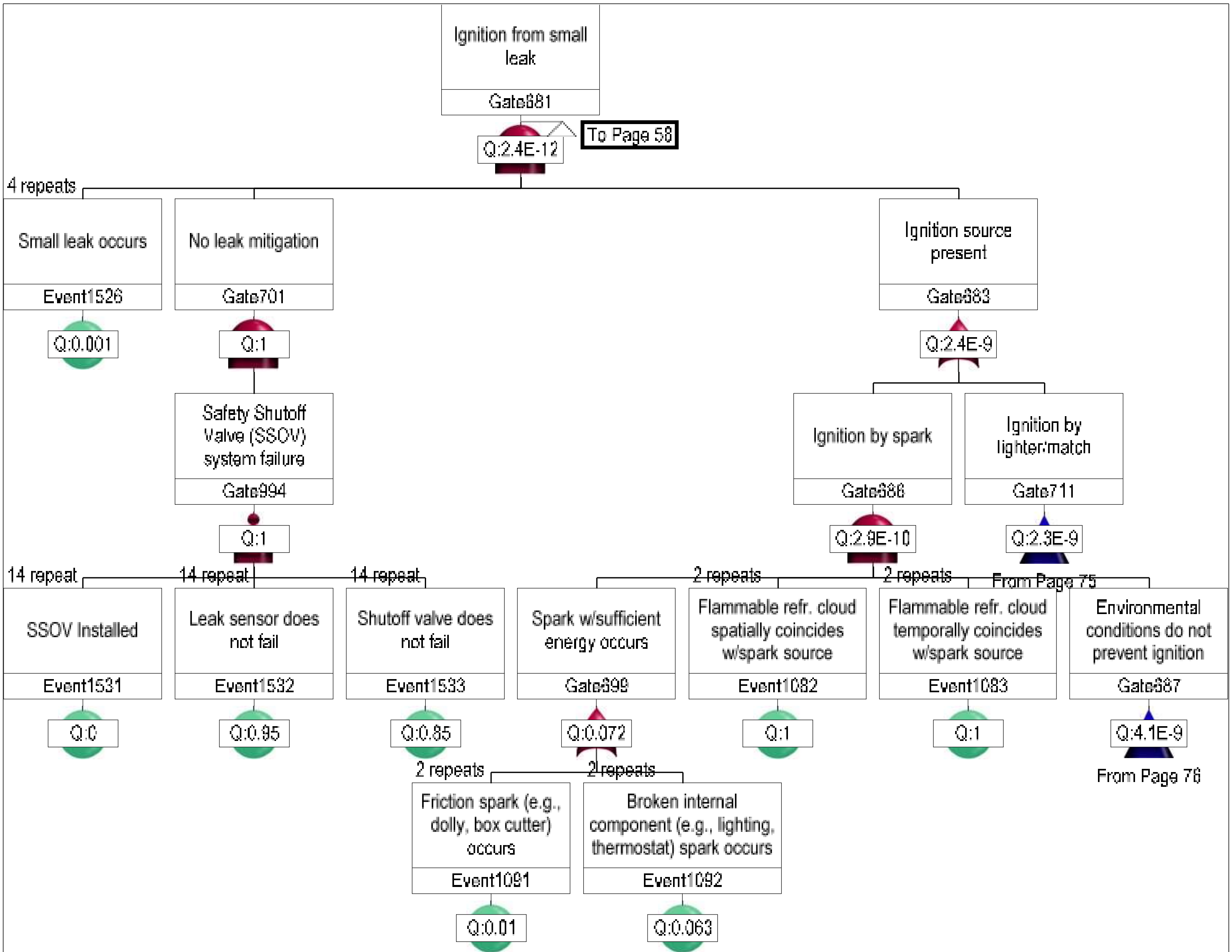



Ignition source present
Gate744
Q:5.4E-9
To Page 57
Ignition by spark
Gate747
Q:1.1E-22
Ignition by lighter/match
Gate748
Q:2.4E-15
Ignition from fees through plug (in condenser)
Gate961
Q:5.4E-9
From Page 72
5 repeats
Spark w/sufficient energy occurs
Gate751
Q:0.042
From Page 73
Flammable refr. cloud spatially coincides w/spark source
Event1253
Q:1E-6
Flammable refr. cloud temporally coincides w/spark source
Event1254
Q:1E-6
Environmental conditions do not prevent ignition
Gate752
Q:2.7E-8
Person uses lighter/match in or near the trailer
Event1124
Q:0.51
Flammable refr. cloud spatially coincides w/flame source
Event1256
Q:1E-4
Flammable refr. cloud temporally coincides w/flame source
Event1257
Q:0.017
Environmental conditions do not prevent ignition
Gate753
Q:2.7E-8
From Page 74
11 repeat
38 repeat
No ignition mitigation
Gate757
Q:4.6E-8
Burning velocity not limiting
Event1265
Q:0.06
Temperature, humidity do not prevent ignition
Event1325
Q:1
10 repeat
23 repeat
Automatic fan not present or fails
Event13292
Q:9.1E-5
Warning signal not present or not heeded
Event1330
Q:5E-4
Automatic shutoff (electronics, compressor/pump) not present or fails
Gate972


Ignition from small leak
Gate681
Q:2.4E-12
To Page 58
4 repeats
Small leak occurs
Event1526
Q:0.001
No leak mitigation
Gate701
Q:1
Ignition source present
Gate683
Q:2.4E-9
Safety Shutoff Valve (SSOV) system failure
Gate994
Q:1
Ignition by spark
Gate686
Q:2.9E-10
Ignition by lighter/match
Gate711
Q:2.3E-9
From Page 75
14 repeat
SSOV Installed
Event1531
Q:0
14 repeat
Leak sensor does not fail
Event1532
Q:0.95
14 repeat
Shutoff valve does not fail
Event1533
Q:0.85
Spark w/sufficient energy occurs
Gate699
Q:0.072
2 repeats
Flammable refr. cloud spatially coincides w/spark source
Event1082
Q:1
2 repeats
Flammable refr. cloud temporally coincides w/spark source
Event1083
Q:1
Environmental conditions do not prevent ignition
Gate687
Q:4.1E-9
From Page 76
2 repeats
Friction spark (e.g., dolly, box cutter) occurs
Event1091
Q:0.01
2 repeats
Broken internal component (e.g., lighting, thermostat) spark occurs
Event1092
Q:0.063

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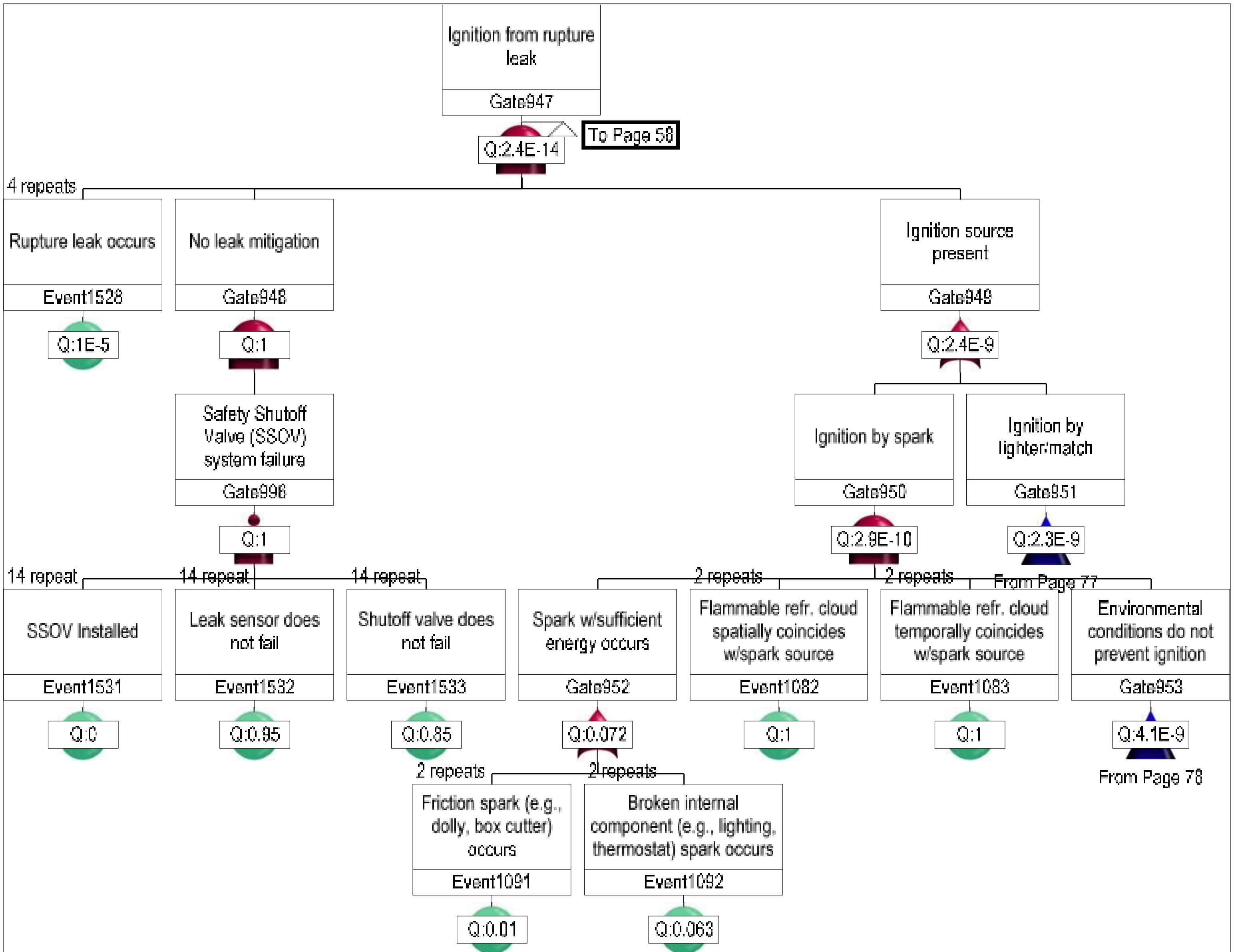
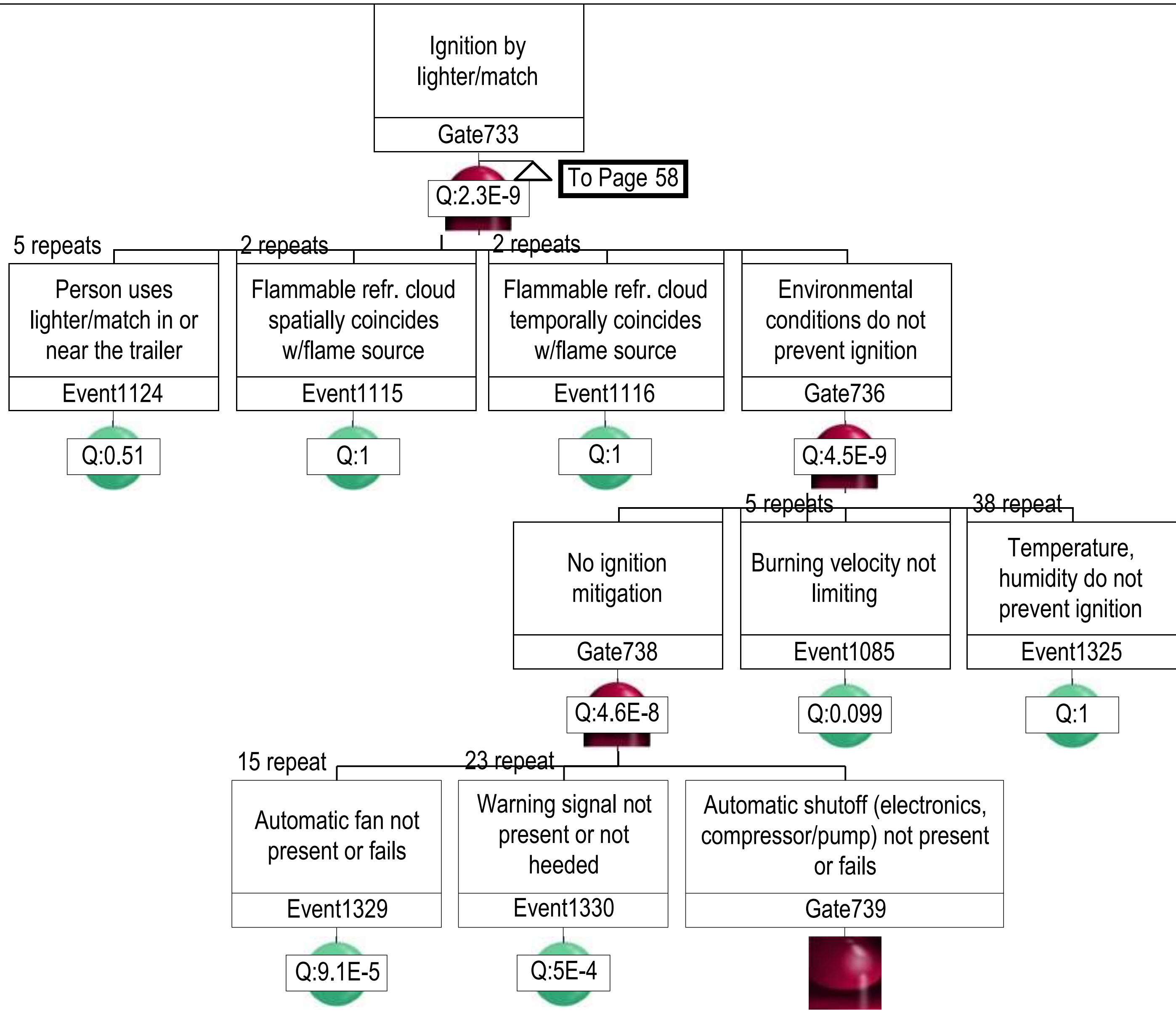
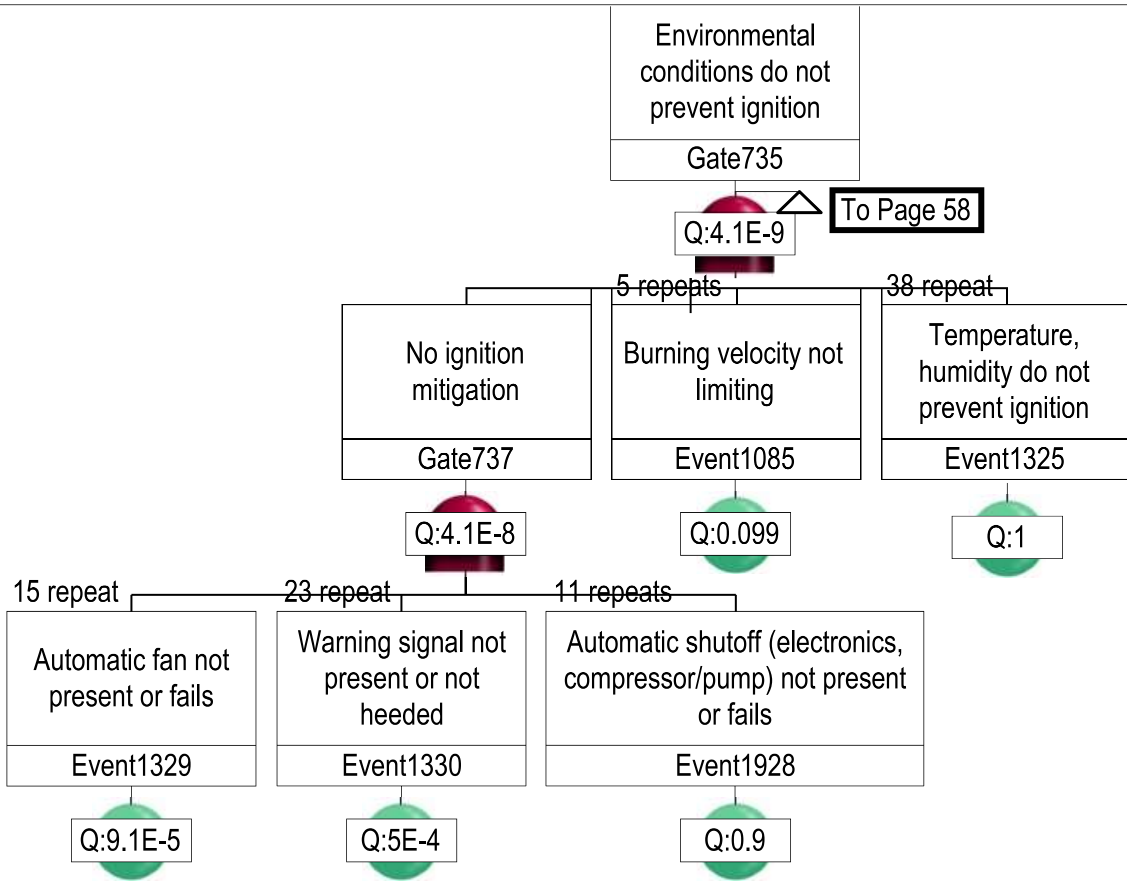
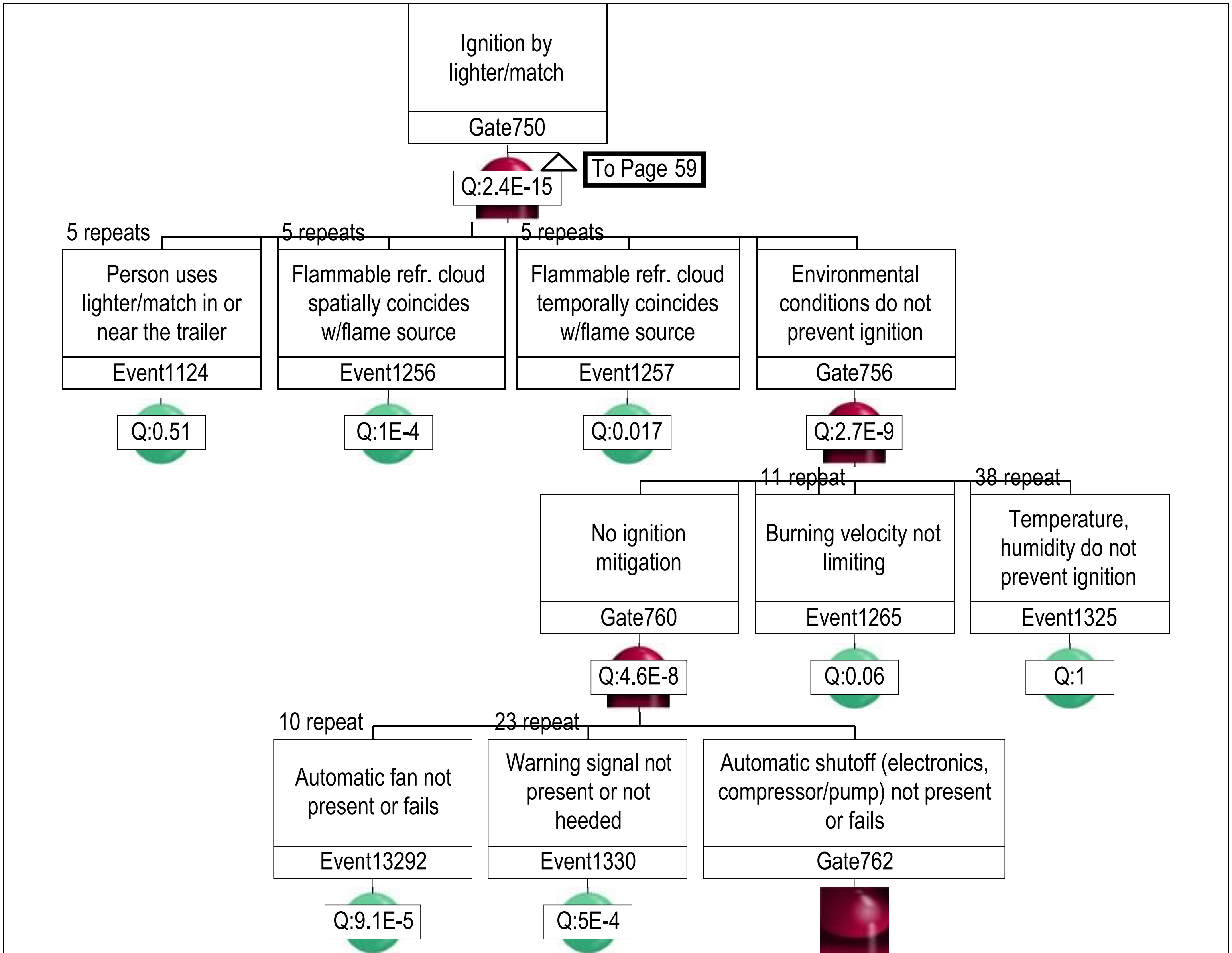
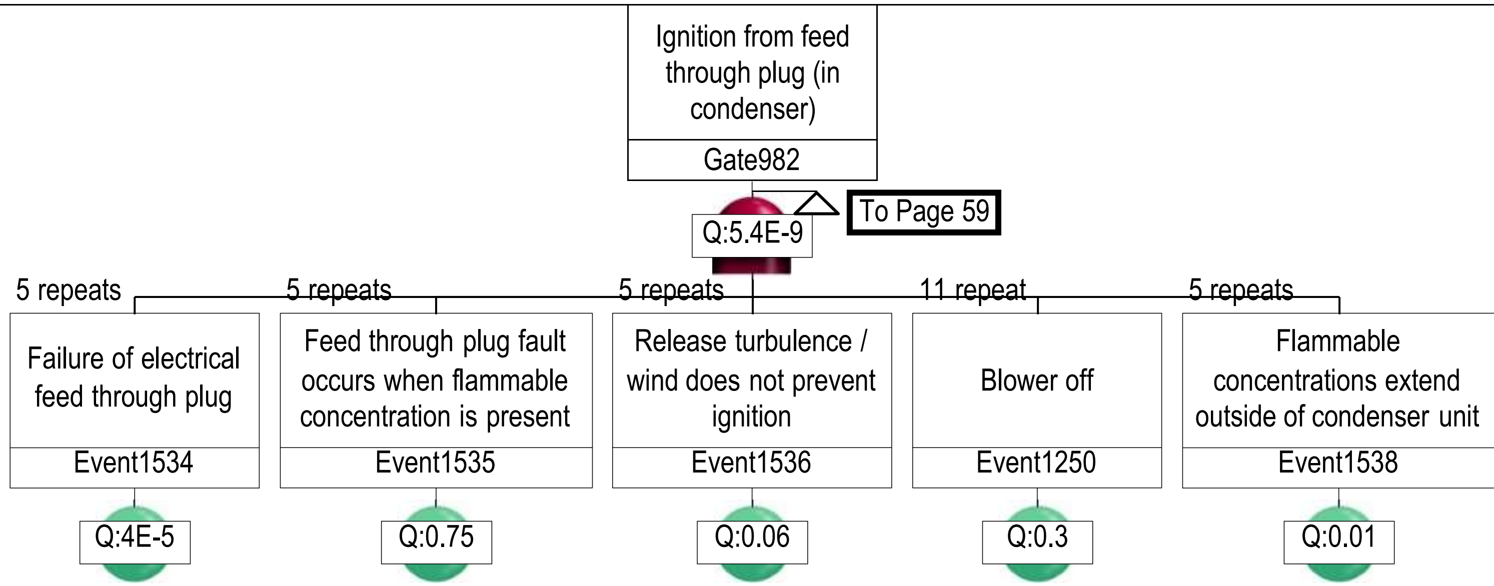


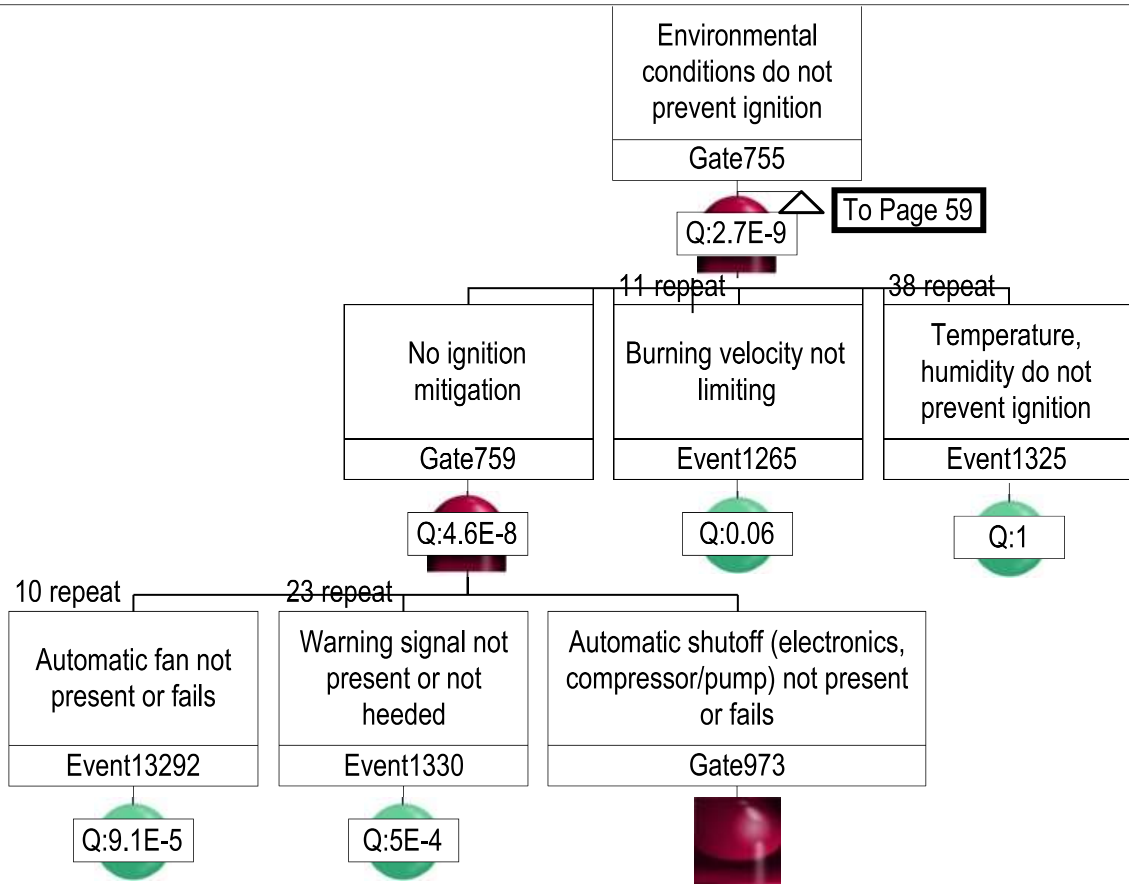

Ignition by lighter/match
Gate733
Q:2.3E-9
To Page 58
5 repeats
2 repeats
2 repeats
Person uses lighter/match in or near the trailer
Event1124
Q:0.51
Flammable refr. cloud spatially coincides w/flame source
Event1115
Q:1
Flammable refr. cloud temporally coincides w/flame source
Event1116
Q:1
Environmental conditions do not prevent ignition
Gate736
Q:4.5E-9
5 repeats
38 repeat
No ignition mitigation
Gate738
Q:4.6E-8
Burning velocity not limiting
Event1085
Q:0.099
Temperature, humidity do not prevent ignition
Event1325
Q:1
15 repeat
23 repeat
Automatic fan not present or fails
Event1329
Q:9.1E-5
Warning signal not present or not heeded
Event1330
Q:5E-4
Automatic shutoff (electronics, compressor/pump) not present or fails
Gate739

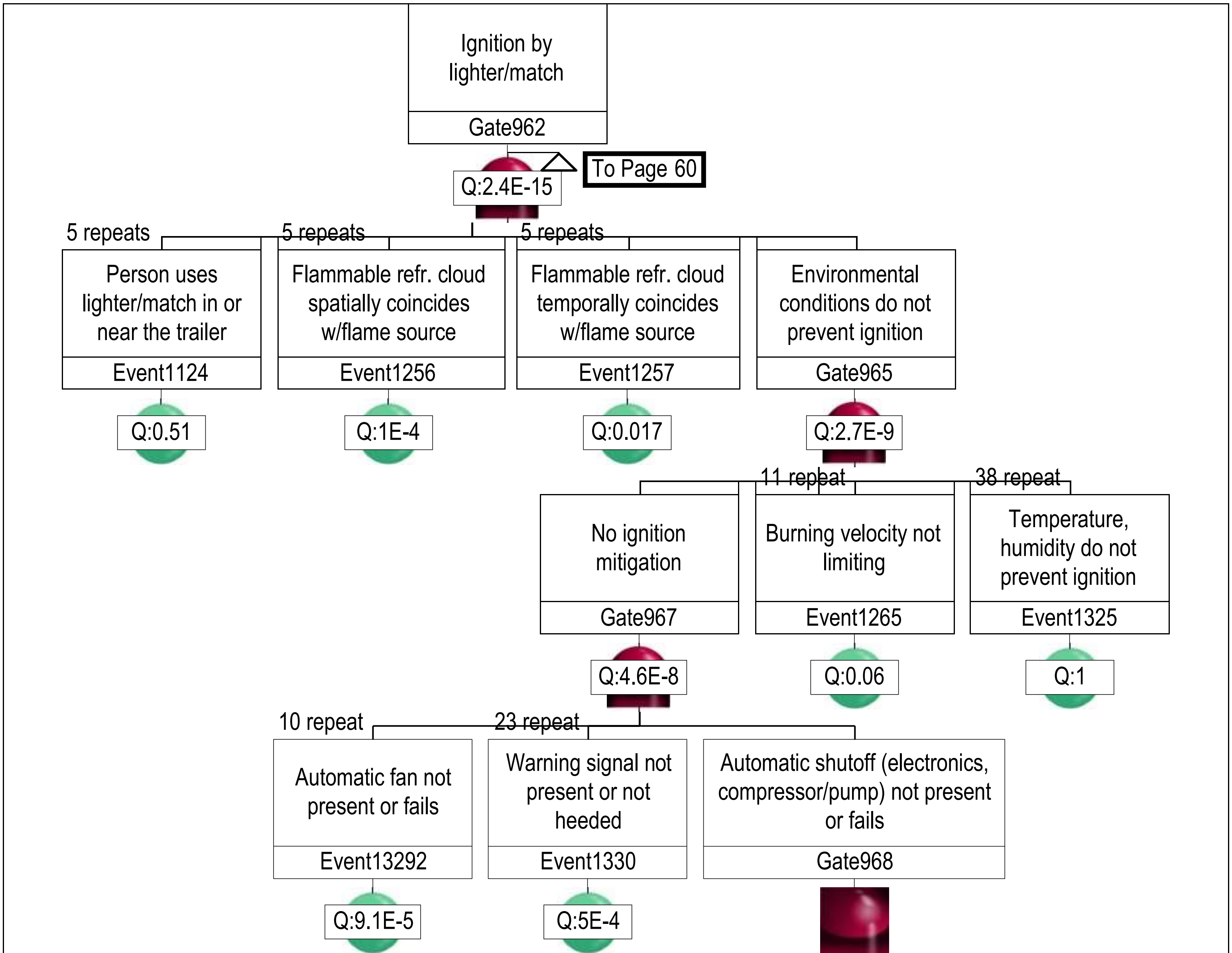

Environmental conditions do not prevent ignition
Gate735
Q:4.1E-9
To Page 58
5 repeats
38 repeat
No ignition mitigation
Gate737
Burning velocity not limiting
Event1085
Temperature, humidity do not prevent ignition
Event1325
Q:4.1E-8
Q:0.099
Q:1
15 repeat
23 repeat
11 repeats
Automatic fan not present or fails
Event1329
Warning signal not present or not heeded
Event1330
Automatic shutoff (electronics, compressor/pump) not present or fails
Event1928
Q:9.1E-5
Q:5E-4
Q:0.9

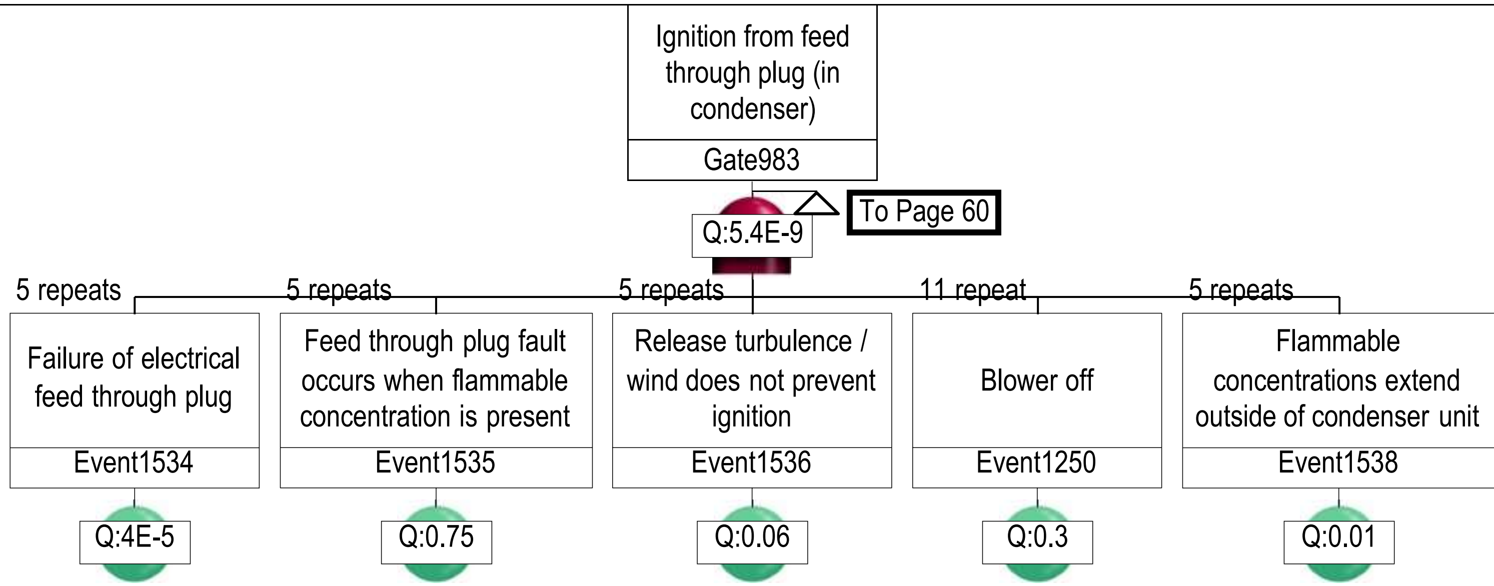

Ignition by lighter/match
Gate750
Q:2.4E-15
To Page 59
5 repeats
5 repeats
5 repeats
Person uses lighter/match in or near the trailer
Event1124
Q:0.51
Flammable refr. cloud spatially coincides w/flame source
Event1256
Q:1E-4
Flammable refr. cloud temporally coincides w/flame source
Event1257
Q:0.017
Environmental conditions do not prevent ignition
Gate756
Q:2.7E-9
11 repeat
38 repeat
No ignition mitigation
Gate760
Q:4.6E-8
Burning velocity not limiting
Event1265
Q:0.06
Temperature, humidity do not prevent ignition
Event1325
Q:1
10 repeat
23 repeat
Automatic fan not present or fails
Event13292
Q:9.1E-5
Warning signal not present or not heeded
Event1330
Q:5E-4
Automatic shutoff (electronics, compressor/pump) not present or fails
Gate762

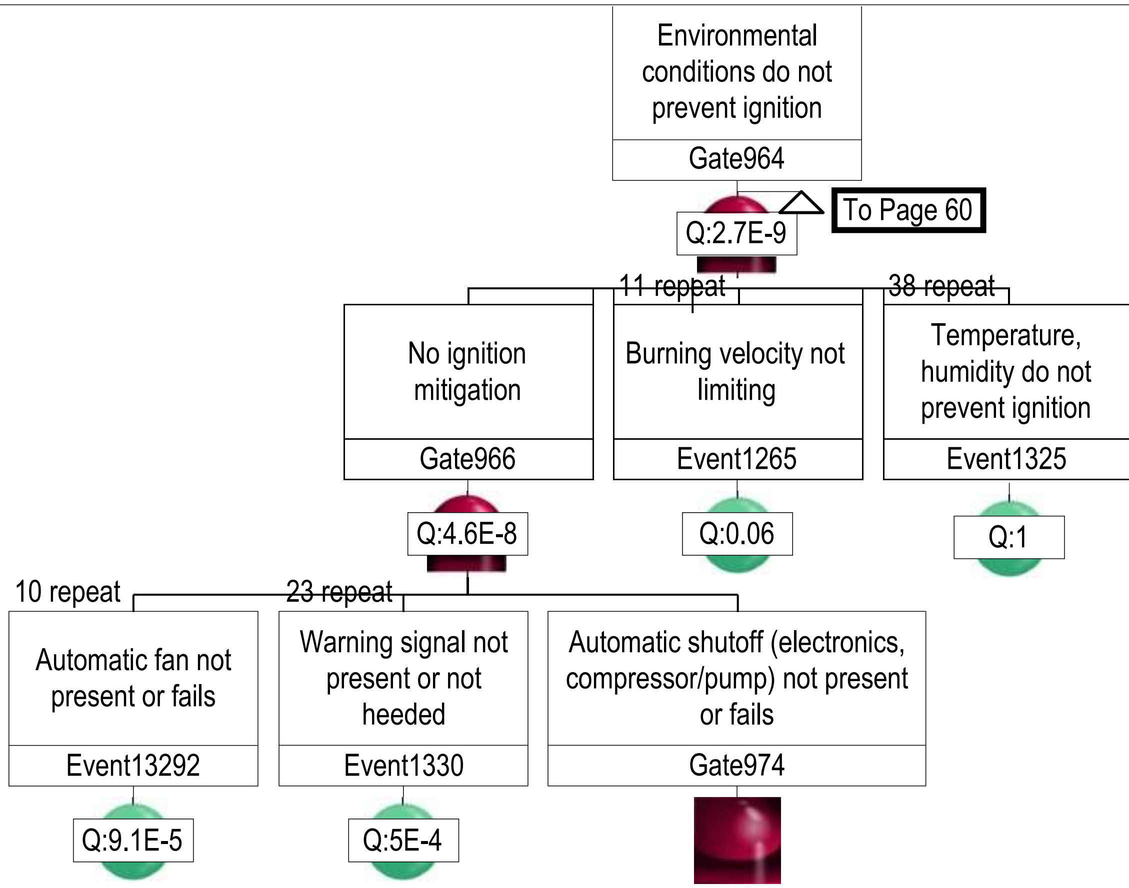

Ignition from feed through plug (in condenser)
Gate982
Q:5.4E-9
To Page 59
5 repeats
Failure of electrical feed through plug
Event1534
Q:4E-5
5 repeats
Feed through plug fault occurs when flammable concentration is present
Event1535
Q:0.75
5 repeats
Release turbulence / wind does not prevent ignition
Event1536
Q:0.06
11 repeat
Blower off
Event1250
Q:0.3
5 repeats
Flammable concentrations extend outside of condenser unit
Event1538
Q:0.01

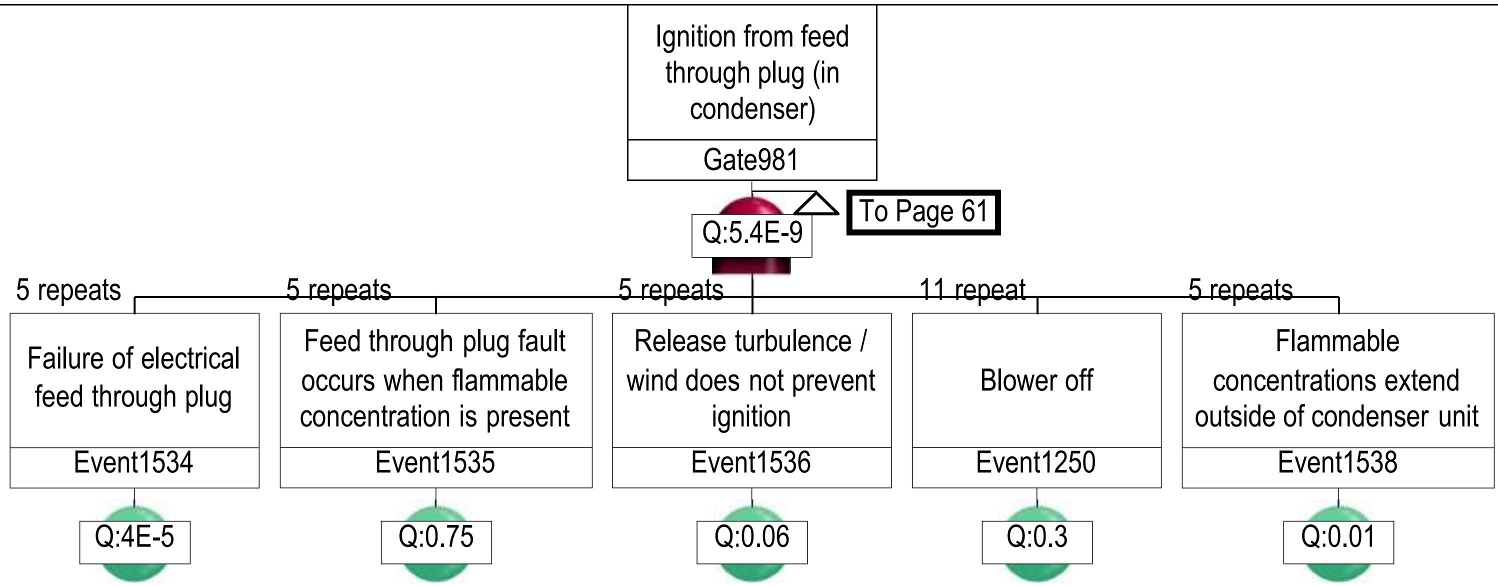
File Name: AHRI-3c-trailer.RFP

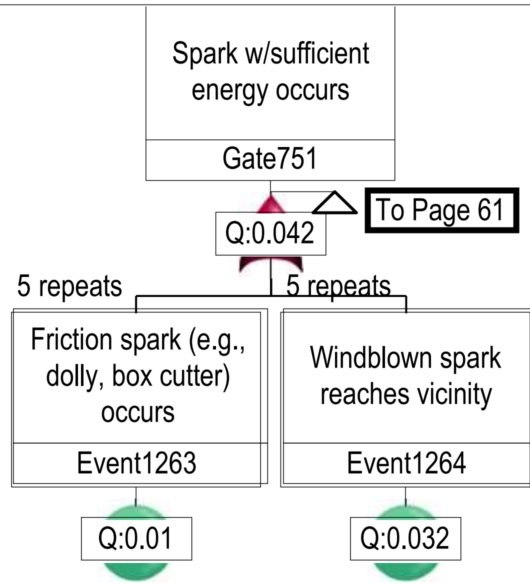


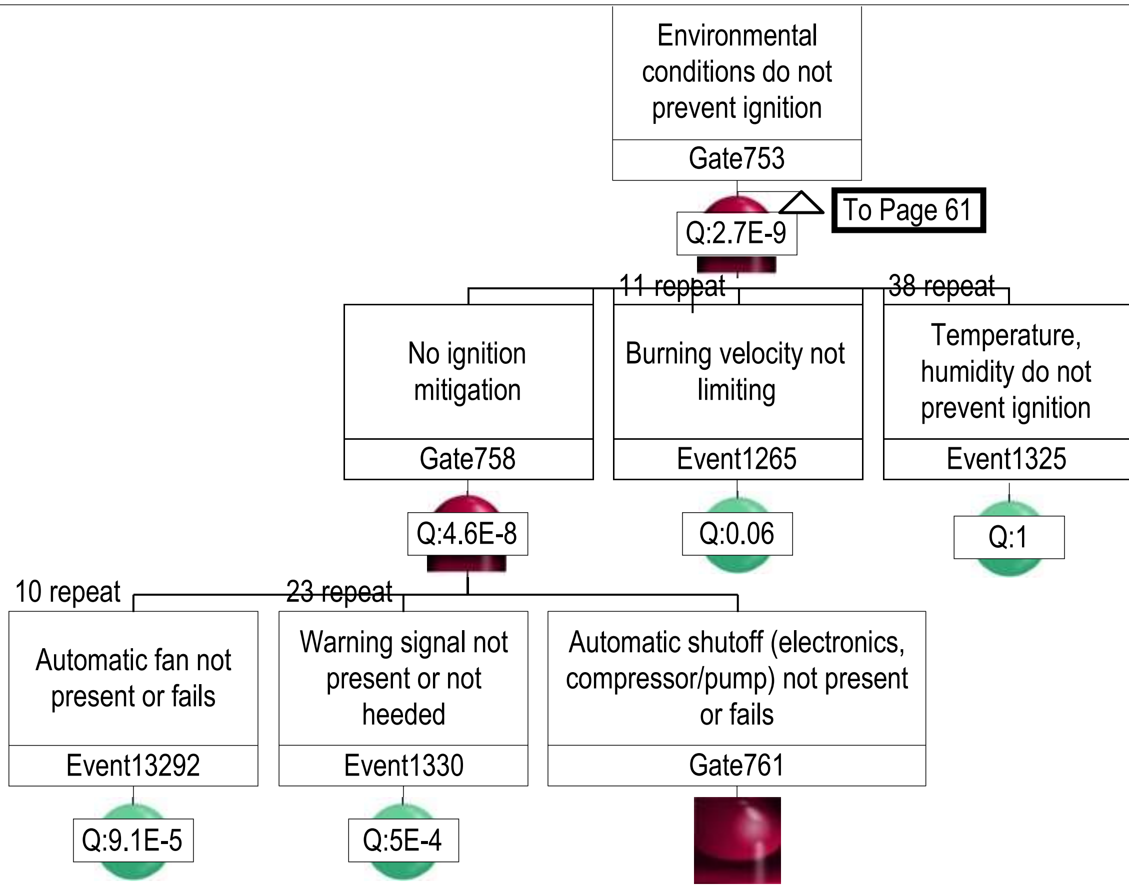

Ignition by lighter/match
Gate962
Q:2.4E-15
To Page 60
5 repeats
5 repeats
5 repeats
Person uses lighter/match in or near the trailer
Event1124
Q:0.51
Flammable refr. cloud spatially coincides w/flame source
Event1256
Q:1E-4
Flammable refr. cloud temporally coincides w/flame source
Event1257
Q:0.017
Environmental conditions do not prevent ignition
Gate965
Q:2.7E-9
11 repeat
38 repeat
No ignition mitigation
Gate967
Q:4.6E-8
Burning velocity not limiting
Event1265
Q:0.06
Temperature, humidity do not prevent ignition
Event1325
Q:1
10 repeat
23 repeat
Automatic fan not present or fails
Event13292
Q:9.1E-5
Warning signal not present or not heeded
Event1330
Q:5E-4
Automatic shutoff (electronics, compressor/pump) not present or fails
Gate968

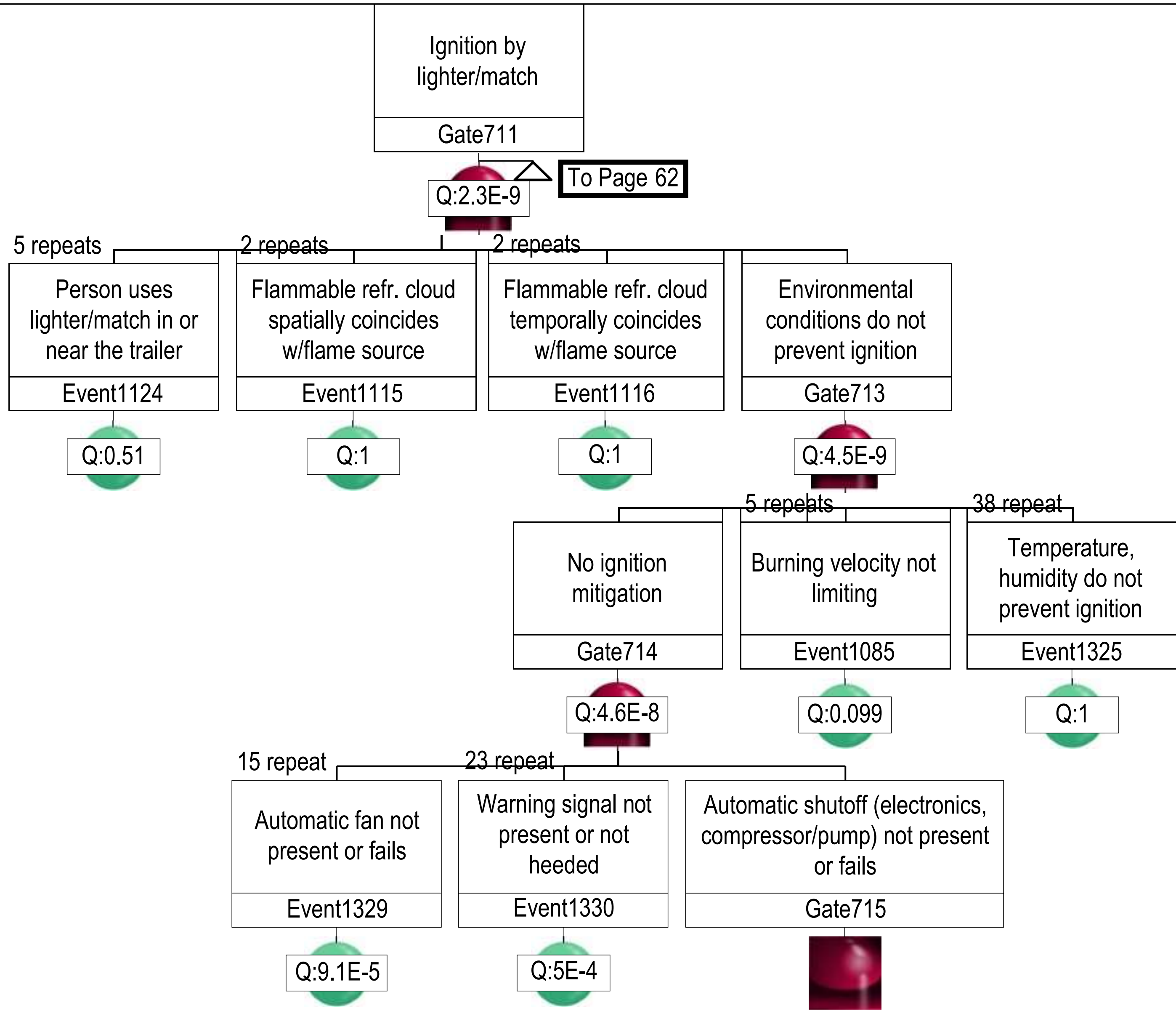

Ignition from feed through plug (in condenser)
Gate983
Q:5.4E-9
To Page 60
5 repeats
Failure of electrical feed through plug
Event1534
Q:4E-5
5 repeats
Feed through plug fault occurs when flammable concentration is present
Event1535
Q:0.75
5 repeats
Release turbulence / wind does not prevent ignition
Event1536
Q:0.06
11 repeat
Blower off
Event1250
Q:0.3
5 repeats
Flammable concentrations extend outside of condenser unit
Event1538
Q:0.01

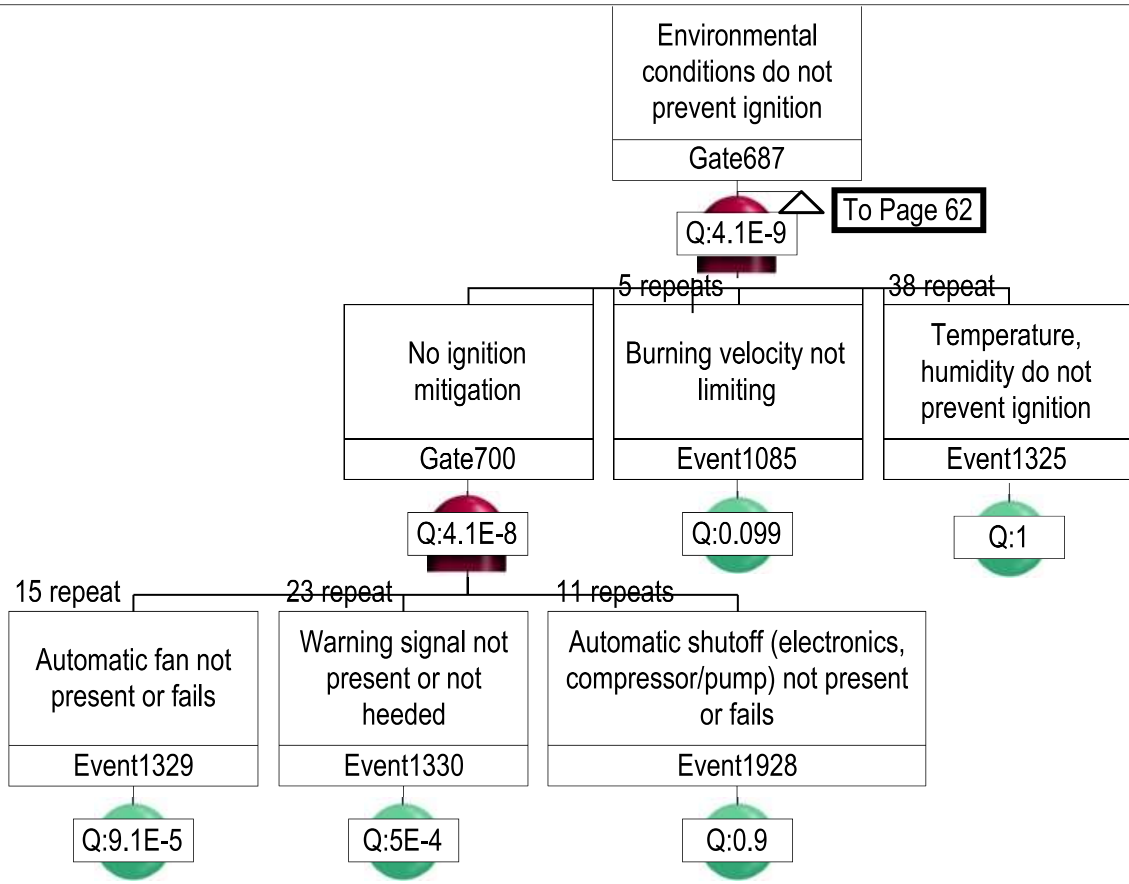

Environmental conditions do not prevent ignition
Gate964
Q:2.7E-9
To Page 60
11 repeat
38 repeat
No ignition mitigation
Gate966
Burning velocity not limiting
Event1265
Temperature, humidity do not prevent ignition
Event1325
Q:4.6E-8
Q:0.06
Q:1
10 repeat
23 repeat
Automatic fan not present or fails
Event13292
Warning signal not present or not heeded
Event1330
Automatic shutoff (electronics, compressor/pump) not present or fails
Gate974
Q:9.1E-5
Q:5E-4


Ignition from feed through plug (in condenser)
Gate981
Q:5.4E-9
To Page 61
5 repeats
5 repeats
5 repeats
11 repeat
5 repeats
Failure of electrical feed through plug
Event1534
Q:4E-5
Feed through plug fault occurs when flammable concentration is present
Event1535
Q:0.75
Release turbulence / wind does not prevent ignition
Event1536
Q:0.06
Blower off
Event1250
Q:0.3
Flammable concentrations extend outside of condenser unit
Event1538
Q:0.01

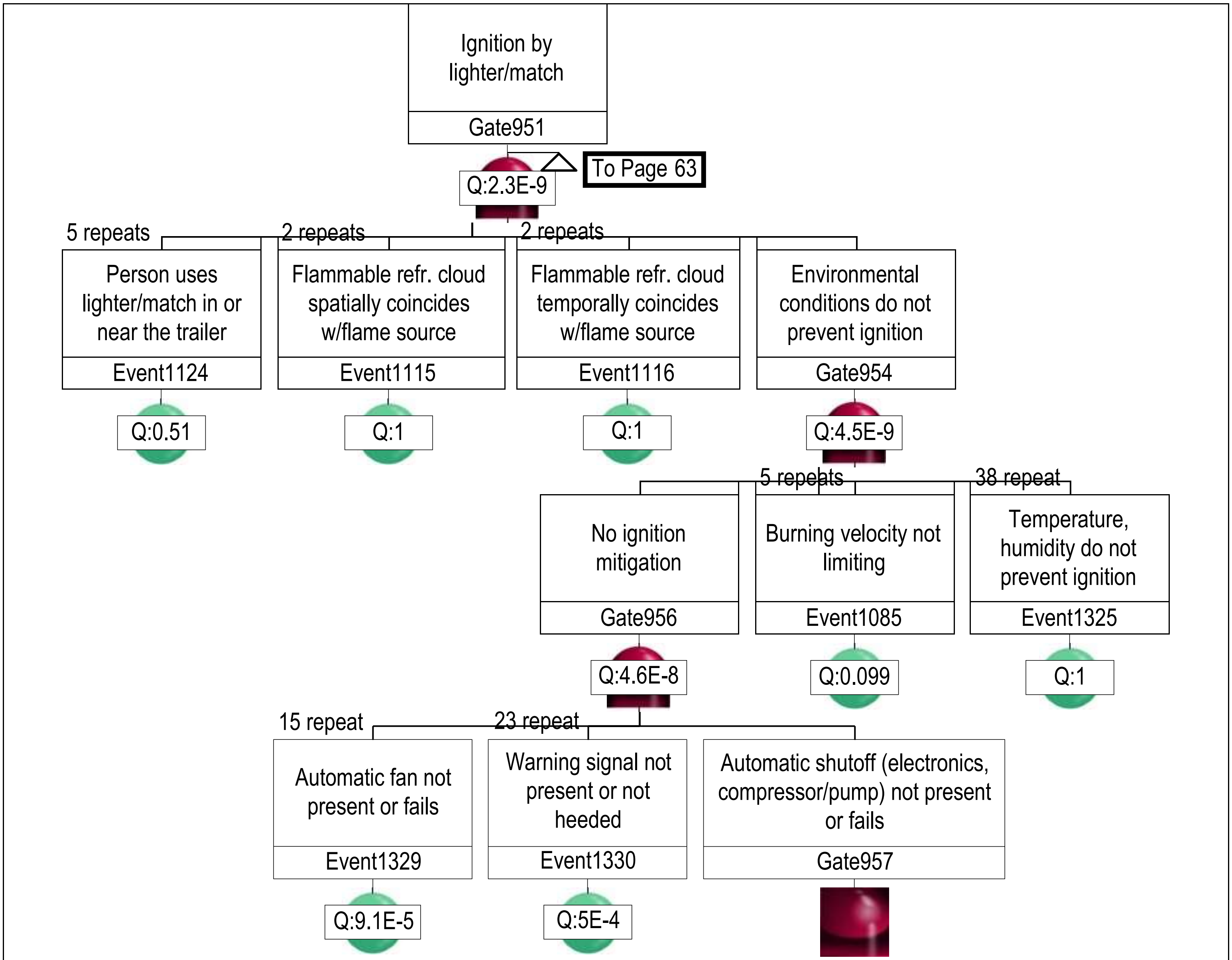

Spark w/sufficient energy occurs
Gate751
To Page 61
Q:0.042
5 repeats
5 repeats
Friction spark (e.g., dolly, box cutter) occurs
Event1263
Windblown spark reaches vicinity
Event1264
Q:0.01
Q:0.032


Environmental conditions do not prevent ignition
Gate753
Q:2.7E-9
To Page 61
11 repeat
38 repeat
No ignition mitigation
Gate758
Q:4.6E-8
Burning velocity not limiting
Event1265
Q:0.06
Temperature, humidity do not prevent ignition
Event1325
Q:1
10 repeat
23 repeat
Automatic fan not present or fails
Event13292
Q:9.1E-5
Warning signal not present or not heeded
Event1330
Q:5E-4
Automatic shutoff (electronics, compressor/pump) not present or fails
Gate761


Ignition by lighter/match
Gate711
Q:2.3E-9
To Page 62
5 repeats
2 repeats
2 repeats
Person uses lighter/match in or near the trailer
Event1124
Q:0.51
Flammable refr. cloud spatially coincides w/flame source
Event1115
Q:1
Flammable refr. cloud temporally coincides w/flame source
Event1116
Q:1
Environmental conditions do not prevent ignition
Gate713
Q:4.5E-9
5 repeats
38 repeat
No ignition mitigation
Gate714
Q:4.6E-8
Burning velocity not limiting
Event1085
Q:0.099
Temperature, humidity do not prevent ignition
Event1325
Q:1
15 repeat
23 repeat
Automatic fan not present or fails
Event1329
Q:9.1E-5
Warning signal not present or not heeded
Event1330
Q:5E-4
Automatic shutoff (electronics, compressor/pump) not present or fails
Gate715


Environmental conditions do not prevent ignition
Gate687
To Page 62
Q:4.1E-9
5 repeats
38 repeat
No ignition mitigation
Gate700
Burning velocity not limiting
Event1085
Temperature, humidity do not prevent ignition
Event1325
Q:4.1E-8
Q:0.099
Q:1
15 repeat
23 repeat
11 repeats
Automatic fan not present or fails
Event1329
Warning signal not present or not heeded
Event1330
Automatic shutoff (electronics, compressor/pump) not present or fails
Event1928
Q:9.1E-5
Q:5E-4
Q:0.9

File Name: AHRI-3c-trailer.RFP



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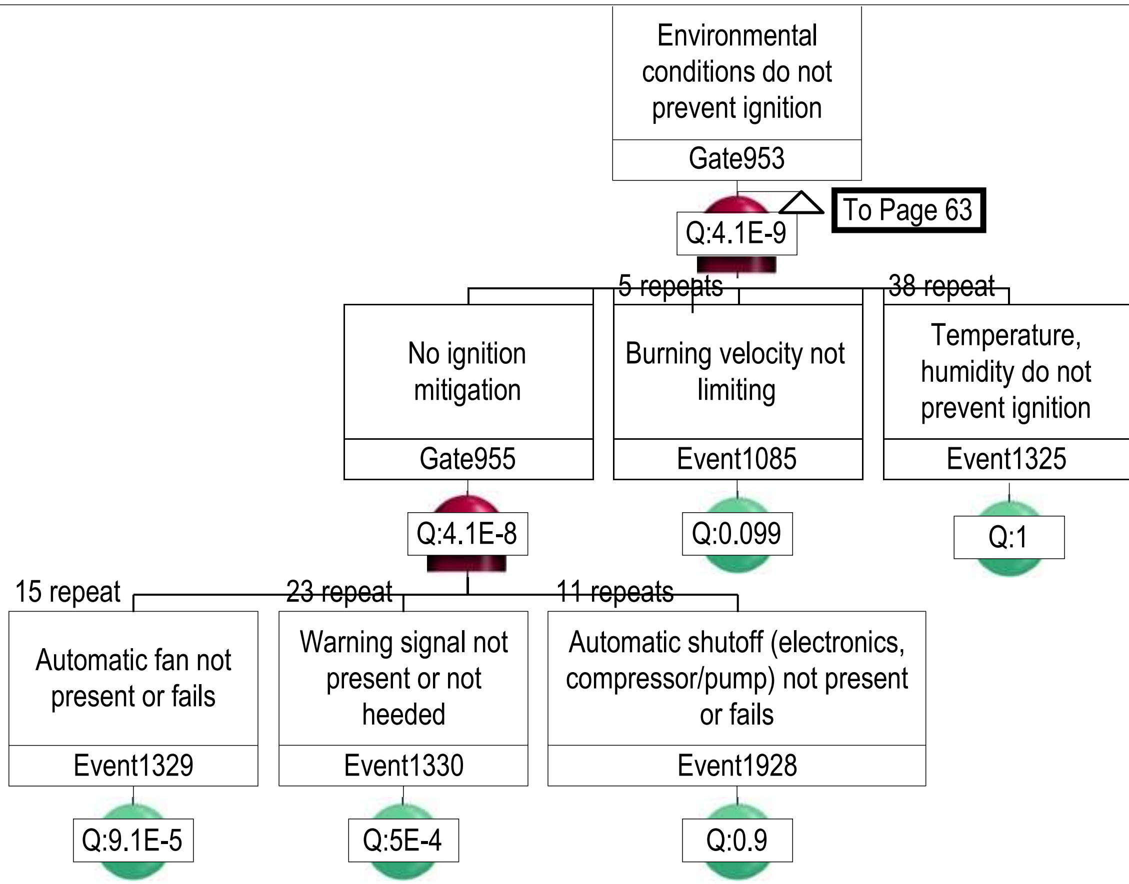

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1075	3-compartment trailer is parked (not in service or (un)loading)	0.81	Times associated with different segments of refrigerated shipping activity are reportedly highly variable. Refrigerated shipping routes over land can be 700-800 miles per haul, and an average of 12 hours was used. Loading and unloading times can be as quick as 30 minutes and can range to many hours; an average of 2 hours for loading and 2 hours for unloading was assumed. Trailers may be parked for around 3 days (72 hr) between hauls. Overall, an average value of 88 hours per shipping 'event' was assumed. These approximate segment times were used to apportion the percentage of time a refrigerated container spends in each part of the cycle. Thus, parking is 72 hr/88 hr or 0.818, the mobile phase is 12 hr/88 hr or 0.136 and loading/unloading is 4 hr/88 hr or 0.0455. Concerning maintenance, on-site surveys report that maintenance occurs at least every 3000 operating hours. Assuming a typical repair job takes 8 hr, this is 8 hr per 3000 operating hour or 0.003. The parking phase is reduced to 0.815 so that all times add up to 1.0.	Basic Event
Event1076	3-compartment trailer is mobile	0.14	Times associated with different segments of refrigerated shipping activity are reportedly highly variable. Refrigerated shipping routes over land can be 700-800 miles per haul, and an average of 12 hours was used. Loading and unloading times can be as quick as 30 minutes and can range to many hours; an average of 2 hours for loading and 2 hours for unloading was assumed. Trailers may be parked for around 3 days (72 hr) between hauls. Overall, an average value of 88 hours per shipping 'event' was assumed. These approximate segment times were used to apportion the percentage of time a refrigerated container spends in each part of the cycle. Thus, parking is 72 hr/88 hr or 0.818, the mobile phase is 12 hr/88 hr or 0.136 and loading/unloading is 4 hr/88 hr or 0.0455. Concerning maintenance, on-site surveys report that maintenance occurs at least every 3000 operating hours. Assuming a typical repair job takes 8 hr, this is 8 hr per 3000 operating hour or 0.003. The parking phase is reduced to 0.815 so that all times add up to 1.0.	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1077	3-compartment trailer is in servicing	0.003	Times associated with different segments of refrigerated shipping activity are reportedly highly variable. Refrigerated shipping routes over land can be 700-800 miles per haul, and an average of 12 hours was used. Loading and unloading times can be as quick as 30 minutes and can range to many hours; an average of 2 hours for loading and 2 hours for unloading was assumed. Trailers may be parked for around 3 days (72 hr) between hauls. Overall, an average value of 88 hours per shipping 'event' was assumed. These approximate segment times were used to apportion the percentage of time a refrigerated container spends in each part of the cycle. Thus, parking is 72 hr/88 hr or 0.818, the mobile phase is 12 hr/88 hr or 0.136 and loading/unloading is 4 hr/88 hr or 0.0455. Concerning maintenance, on-site surveys report that maintenance occurs at least every 3000 operating hours. Assuming a typical repair job takes 8 hr, this is 8 hr per 3000 operating hour or 0.003. The parking phase is reduced to 0.815 so that all times add up to 1.0.	Basic Event
Event1078	3-compartment trailer is being (un)loaded	0.04	Times associated with different segments of refrigerated shipping activity are reportedly highly variable. Refrigerated shipping routes over land can be 700-800 miles per haul, and an average of 12 hours was used. Loading and unloading times can be as quick as 30 minutes and can range to many hours; an average of 2 hours for loading and 2 hours for unloading was assumed. Trailers may be parked for around 3 days (72 hr) between hauls. Overall, an average value of 88 hours per shipping 'event' was assumed. These approximate segment times were used to apportion the percentage of time a refrigerated container spends in each part of the cycle. Thus, parking is 72 hr/88 hr or 0.818, the mobile phase is 12 hr/88 hr or 0.136 and loading/unloading is 4 hr/88 hr or 0.0455. Concerning maintenance, on-site surveys report that maintenance occurs at least every 3000 operating hours. Assuming a typical repair job takes 8 hr, this is 8 hr per 3000 operating hour or 0.003. The parking phase is reduced to 0.815 so that all times add up to 1.0.	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1526	Small leak occurs	0.001	ISO 20854 Annex D reports small leak frequencies in container refrigeration systems as less than 1E-3 per year.	Basic Event
Event1531	SSOV Installed	0	Fault tree analysis will be conducted two ways: assuming a safety shutoff valve is present (value = 1) and assuming a safety shutoff valve is not present (value = 0).	Basic Event
Event1532	Leak sensor does not fail	0.95	The NPRD reports an overall failure rate for a "gas detector" as <5.8 per million operating hours, i.e., no actual failures were reported in the observed operating times. The bound of 5.8 per million operating hours, equivalent to 0.05 per year assuming continuous operation of the safety shutoff system, was used as the failure rate, so 1-0.05 = 0.95 is the probability that the sensor does not fail.	Basic Event
Event1533	Shutoff valve does not fail	0.85	The NPRD reports an overall failure rate for a "shutoff valve" of 17.4 per million operating hours, or 0.15 per year assuming continuous operation of the safety shutoff system, so 1-0.15 = 0.85 is the probability that the shutoff valve does not fail.	Basic Event
Event1319	Vehicle accident causes damaged wire w/sufficient energy	1E-10	SAE CRP evaluations have determined that substantial damage is required to a passenger vehicle before a reasonable portion of wire would be exposed. Values of 1E-6 to 1E-3 were used as the frequency in the event of a collision, depending on the severity and location of the vehicle collision. 1E-10 is used here, reflecting the combination of the low likelihood of severe collisions as well as the range in frequency of damaged wires occurring in the event of a collision.	Basic Event
Event1320	Flammable refr. cloud spatially coincides w/wire source	1	Based on analytical calculations and CFD modeling, releases into a 3-compartment trailer are expected to distribute relatively evenly soon after the leak and achieve flammable concentrations throughout the trailer, thus they would spatially coincide with a wire source that might occur.	Basic Event
Event1321	Flammable refr. cloud temporally coincides w/wire source	1	Releases into a 3-compartment trailer are expected to reach a flammable concentration and stay at that concentration for a very long time due to the tightness of the compartment (while doors are closed). Thus a hot wire occurring at any time after the release would coincide with time of a flammable concentration.	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1329	Automatic fan not present or fails	0.000091	The EPRD lists failure rates for integrated circuit digital controllers as 7/676.687 per million hours, or 9E-5 failures per year. No failures were reported specifically for ground mobile (i.e., transport vehicle) applications, so this value is expected to be conservative. It is assumed that all vehicles have an automatic fan present as a mitigation measure.	Basic Event
Event1330	Warning signal not present or not heeded	0.0005	A typical human error rate for a person ignoring a warning signal is 1E-3 (Blackman et al., 2008), however a warning signal may also not be present in the container, so half the value is used.	Basic Event
Event1928	Automatic shutoff (electronics, compressor/pump) not present or fails	0.9	The EPRD lists failure rates for integrated circuit digital controllers as 7/676.687 per million hours, or 9E-5 failures per year. No failures were reported specifically for ground mobile (i.e., transport vehicle) applications, so this value is expected to be conservative. Not all vehicles will have automatic shutoffs to power down electronics, however. It is assumed that only 10% of vehicles may have such automatic shutoffs.	Basic Event
Event1324	Burning velocity not limiting	0.99	Over a long period of time, velocities following a release of refrigerant into the refrigerated compartment will approach low values, and burning velocity is only expected to be limiting in the few minutes following an initial release	Basic Event
Event1325	Temperature, humidity do not prevent ignition	1	The impacts of temperature and humidity on refrigerant ignition are refrigerant dependent. For R-516a, temperature and humidity are not expected to be limiting.	Basic Event
Event1326	Broken internal component (e.g., lighting, thermostat) spark occurs	0.00026	According to the US NRC, the typical failure rate for wire shorts is 3E-7 per operating hour. Assuming 2 pieces of electrical equipment are in the container yields a frequency of 5.3E-3 per year (8766 hr/yr * 3E-7/hr). Whether a spark has sufficient energy is dependent on the refrigerant of interest. The probability that an electrical short has sufficient energy to ignite R-516A is low, given the energy of sparks is 20 to 30 mJ (ACC, 2007) and the MIE for R-516A is 81 mJ. The calculated probability of 5.3E-3 was adjusted by a factor of 0.05.	Basic Event
Gate838	Ignition by collision/friction sparks		Collision/friction sparks occur too early to ignite refrigerant released from a trailer condenser.	Remarks Gate

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1322	Flammable refr. cloud spatially coincides w/spark source	1	Based on analytical calculations and CFD modeling, releases into a 3-compartment trailer are expected to distribute relatively evenly soon after the leak and achieve flammable concentrations throughout the trailer, thus they would spatially coincide with a spark that might occur.	Basic Event
Event1323	Flammable refr. cloud temporally coincides w/spark source	1	Releases into a 3-compartment trailer are expected to reach a flammable concentration and stay at that concentration for a very long time due to the tightness of the compartment (while doors are closed). Thus a spark occurring at any time after the release would coincide with time of a flammable concentration.	Basic Event
Event1327	Burning velocity not limiting	0.99	Over a long period of time, velocities following a release of refrigerant into the refrigerated compartment will approach low values, and burning velocity is only expected to be limiting in the few minutes following an initial release	Basic Event
Event1527	Large leak occurs	0.0001	ISO 20854 Annex D reports large leak frequencies in container refrigeration systems as less than 1E-4 per year.	Basic Event
Event1296	Flammable refr. cloud spatially coincides w/wire source	1	Based on analytical calculations and CFD modeling, releases into a 3-compartment trailer are expected to distribute relatively evenly soon after the leak and achieve flammable concentrations throughout the trailer, thus they would spatially coincide with a wire source that might occur.	Basic Event
Event1297	Flammable refr. cloud temporally coincides w/wire source	1	Releases into a 3-compartment trailer are expected to reach a flammable concentration and stay at that concentration for a very long time due to the tightness of the compartment (while doors are closed). Thus a hot wire occurring at any time after the release would coincide with time of a flammable concentration.	Basic Event
Event1299	Burning velocity not limiting	0.99	Over a long period of time, velocities following a release of refrigerant into the refrigerated compartment will approach low values, and burning velocity is only expected to be limiting in the few minutes following an initial release	Basic Event
Gate693	Ignition by collision/friction sparks		Collision/friction sparks occur too early to ignite refrigerant released from a trailer condenser.	Remarks Gate

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1305	Flammable refr. cloud spatially coincides w/spark source	1	Based on analytical calculations and CFD modeling, releases into a 3-compartment trailer are expected to distribute relatively evenly soon after the leak and achieve flammable concentrations throughout the trailer, thus they would spatially coincide with a spark that might occur.	Basic Event
Event1306	Flammable refr. cloud temporally coincides w/spark source	1	Releases into a 3-compartment trailer are expected to reach a flammable concentration and stay at that concentration for a very long time due to the tightness of the compartment (while doors are closed). Thus a spark occurring at any time after the release would coincide with time of a flammable concentration.	Basic Event
Event1308	Burning velocity not limiting	0.99	Over a long period of time, velocities following a release of refrigerant into the refrigerated compartment will approach low values, and burning velocity is only expected to be limiting in the few minutes following an initial release	Basic Event
Event1528	Rupture leak occurs	0.00001	ISO 20854 Annex D reports rupture leak frequencies in container refrigeration systems as much less than 1E-5 per year. 1E-5 was used to be conservative.	Basic Event
Event1445	Flammable refr. cloud spatially coincides w/wire source	1	Based on analytical calculations and CFD modeling, releases into a 3-compartment trailer are expected to distribute relatively evenly soon after the leak and achieve flammable concentrations throughout the trailer, thus they would spatially coincide with a wire source that might occur.	Basic Event
Event1446	Flammable refr. cloud temporally coincides w/wire source	1	Releases into a 3-compartment trailer are expected to reach a flammable concentration and stay at that concentration for a very long time due to the tightness of the compartment (while doors are closed). Thus a hot wire occurring at any time after the release would coincide with time of a flammable concentration.	Basic Event
Event1449	Burning velocity not limiting	0.99	Over a long period of time, velocities following a release of refrigerant into the refrigerated compartment will approach low values, and burning velocity is only expected to be limiting in the few minutes following an initial release	Basic Event
Gate927	Ignition by collision/friction sparks		Collision/friction sparks occur too early to ignite refrigerant released from a trailer condenser.	Remarks Gate

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1447	Flammable refr. cloud spatially coincides w/spark source	1	Based on analytical calculations and CFD modeling, releases into a 3-compartment trailer are expected to distribute relatively evenly soon after the leak and achieve flammable concentrations throughout the trailer, thus they would spatially coincide with a spark that might occur.	Basic Event
Event1448	Flammable refr. cloud temporally coincides w/spark source	1	Releases into a 3-compartment trailer are expected to reach a flammable concentration and stay at that concentration for a very long time due to the tightness of the compartment (while doors are closed). Thus a spark occurring at any time after the release would coincide with time of a flammable concentration.	Basic Event
Event1452	Burning velocity not limiting	0.99	Over a long period of time, velocities following a release of refrigerant into the refrigerated compartment will approach low values, and burning velocity is only expected to be limiting in the few minutes following an initial release	Basic Event
Gate689	Ignition from leak outside 3-compartment trailer (condenser)		Ignition not plausible outside in a mobile situation. While prior assessments have identified potential risks from releases outside of the cabin/interior area for vehicles, the releases have occurred in sheltered engine compartment areas and were found to be negligible when the engine compartment was opened as part of a collision, due to the natural outdoor air currents.	Remarks Gate
Event1210	Flammable refr. cloud spatially coincides w/spark source	1	Based on analytical calculations and CFD modeling, releases into a 3-compartment trailer are expected to distribute relatively evenly soon after the leak and achieve flammable concentrations throughout the trailer, thus they would spatially coincide with a spark that might occur.	Basic Event
Event1211	Flammable refr. cloud temporally coincides w/spark source	1	Releases into a 3-compartment trailer are expected to reach a flammable concentration and stay at that concentration for a very long time due to the tightness of the compartment (while doors are closed). Thus a spark occurring at any time after the release would coincide with time of a flammable concentration.	Basic Event
Event1222	Burning velocity not limiting	0.99	Over a long period of time, velocities following a release of refrigerant into the refrigerated compartment will approach low values, and burning velocity is only expected to be limiting in the few minutes following an initial release	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1215	Flammable refr. cloud spatially coincides w/spark source	1	Based on analytical calculations and CFD modeling, releases into a 3-compartment trailer are expected to distribute relatively evenly soon after the leak and achieve flammable concentrations throughout the trailer, thus they would spatially coincide with a spark that might occur.	Basic Event
Event1216	Flammable refr. cloud temporally coincides w/spark source	1	Releases into a 3-compartment trailer are expected to reach a flammable concentration and stay at that concentration for a very long time due to the tightness of the compartment (while doors are closed). Thus a spark occurring at any time after the release would coincide with time of a flammable concentration.	Basic Event
Event1228	Burning velocity not limiting	0.99	Over a long period of time, velocities following a release of refrigerant into the refrigerated compartment will approach low values, and burning velocity is only expected to be limiting in the few minutes following an initial release	Basic Event
Event1462	Flammable refr. cloud spatially coincides w/spark source	1	Based on analytical calculations and CFD modeling, releases into a 3-compartment trailer are expected to distribute relatively evenly soon after the leak and achieve flammable concentrations throughout the trailer, thus they would spatially coincide with a spark that might occur.	Basic Event
Event1463	Flammable refr. cloud temporally coincides w/spark source	1	Releases into a 3-compartment trailer are expected to reach a flammable concentration and stay at that concentration for a very long time due to the tightness of the compartment (while doors are closed). Thus a spark occurring at any time after the release would coincide with time of a flammable concentration.	Basic Event
Event1465	Burning velocity not limiting	0.99	Over a long period of time, velocities following a release of refrigerant into the refrigerated compartment will approach low values, and burning velocity is only expected to be limiting in the few minutes following an initial release	Basic Event
Event1250	Blower off	0.3	It is assumed that the blower operates 30% of the time. Units cycle on and off, although the total amount of run time will vary based on trailer design, climate, and temperature control needs.	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1263	Friction spark (e.g., dolly, box cutter) occurs	0.01	Friction sparks are expected to occur frequently external to a refrigerated trailer from dolly activity and other commercial/industrial operations. Most sparks are in the range of 20-30 mJ (ACC, 2007), so it would require a very high energy spark to exceed the R-516A MIE of 81 mJ. Only 1% or less of sparks are expected to exceed this threshold.	Basic Event
Event1264	Windblown spark reaches vicinity	0.03	Windblown embers can be carried for miles from a wildfire. Verisk reports that 4.5 million of the 139 million homes in the US are at risk for wildfire, including from windblown embers, which is a very conservative proxy for the fraction of developed areas where a trailer may be parked in the vicinity of a windblown spark.	Basic Event
Event1253	Flammable refr. cloud spatially coincides w/spark source	0.000001	A windblown spark or ember would need to land very near to an outdoor condenser leak in order to coincide with a flammable cloud, which would be dispersed by the same wind bringing the windblown spark/ember. Such an event is expected to be a rare (1 in a million or less) occurrence.	Basic Event
Event1254	Flammable refr. cloud temporally coincides w/spark source	0.000001	A leak of sufficient rate to produce a flammable cloud of refrigerant outdoors, under windy conditions, would be very short in duration before the charge was depleted. The timing of a spark/ember coinciding with such a leak is expected to be a rare (1 in a million or less) occurrence.	Basic Event
Event1276	Warning signal not present or not heeded	0.5	When a trailer is parked, but not being loaded or unloaded, attentive personnel may not be in the vicinity of the vehicle, and a warning signal is much more likely to go unnoticed.	Basic Event
Gate969	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent a windblown or external spark source.	Remarks Gate
Event1265	Burning velocity not limiting	0.06	The low burning velocity (4.75 cm/s, or 0.1 mph) is likely to be exceeded in all but still air conditions, which occur in the US 6% of the time (see Gradient, 2015). Will vary by geographic region.	Basic Event
Event1255	Person uses lighter/match near the trailer	0.51	Data from the CDC indicate that approximately 51% of long-haul truck drivers smoke (CDC, 2015).	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1256	Flammable refr. cloud spatially coincides w/flame source	0.0001	While it is possible that a smoker climbs onto the roof of a truck and lights a cigarette near a leaking condenser, in general it is expected that smokers will light cigarettes on the ground, where a flammable concentration of refrigerant is unlikely to accumulate to the highly dispersive outdoor setting. A value of 1E-4 is used.	Basic Event
Event1257	Flammable refr. cloud temporally coincides w/flame source	0.02	A match takes 5 seconds to strike and light a cigarette. A butane lighter would be similar. A cigarette takes about 5 minutes to smoke. Conservatively assuming one smoker is always smoking near the vehicle while it is parked, lighting events would occur 1/60 of the time.	Basic Event
Event13292	Automatic fan not present or fails	0.000091	The EPRD lists failure rates for integrated circuit digital controllers as 7/676.687 per million hours, or 9E-5 failures per year. No failures were reported specifically for ground mobile (i.e., transport vehicle) applications, so this value is expected to be conservative. It is assumed that all vehicles have an automatic fan present as a mitigation measure.	Basic Event
Gate810	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent someone from striking a match or igniting a lighter.	Remarks Gate
Event1534	Failure of electrical feed through plug	0.00004	RIAC NPRD (2011) database failure rate for electrical feed through connectors was 4E-5/year.	Basic Event
Event1535	Feed through plug fault occurs when flammable concentration is present	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.	Basic Event
Event1536	Release turbulence / wind does not prevent ignition	0.06	The low burning velocity (4.75 cm/s, or 0.1 mph) is likely to be exceeded in all but still air conditions, which occur in the US 6% of the time (see Gradient, 2015). Will vary by geographic region.	Basic Event
Event1538	Flammable concentrations extend outside of condenser unit	0.01	Prior modeling of releases from condensers into outdoor scenarios has shown that flammable concentrations are not expected to persist beyond the condenser unit (see AHRI, 2015).	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Gate970	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent a windblown or external spark source.	Remarks Gate
Gate811	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent someone from striking a match or igniting a lighter.	Remarks Gate
Gate976	Ignition from vandalism		As reported in Gradient (2019), Ahrens [NFPA], 2008 reported that 8% of all vehicle fires (with a total probability 1.22E-3) were intentional, i.e., due to vandalism. However, these events are unrelated to the refrigeration system, and were not included in the FTA. They do provide a reference for comparative risk.	Remarks Gate
Gate971	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent a windblown or external spark source.	Remarks Gate
Gate946	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent someone from striking a match or igniting a lighter.	Remarks Gate
Event1335	Servicing refrigeration system occurs indoors	0.16	Interviews with service center personnel indicated that a substantial portion of repair work occurs outdoors. In this analysis, we assumed that 80% of the work occurs outdoors and 20% occurs indoors. The servicing work at the facilities visited was reported to be 20% non-refrigeration-related and 80% refrigeration-related. Thus, the probability of servicing the refrigeration system indoors is 20% * 80% = 0.16.	Basic Event
Event1336	Refrigerant release from issue prior to servicing (incomplete discharge)	0.25	Interviews with service center personnel indicated that trailers generally return empty, since the systems reportedly continue to function well even with half a charge or less, although other service center personnel reported that only about half of the products to be serviced contain no charge when brought in. Not all vehicles that are leaking will lead to a flammable concentration, however, and a value of 0.25 is used based on discussion with the AHRI PMS. A value of 0.25 indicates that half of the units returning empty (using the upper end of the estimates) leak sufficiently to produce a flammable concentration.	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1530	Serviceperson intentionally vents refrigerant	0.0001	Interviews with service center personnel indicated that refrigerants are never intentionally vented to the atmosphere. Service center personnel also go through training before starting work. Thus the probability for human error in individuals with specialized training, 1E-4 (Blackman et al., 2008), is used.	Basic Event
Event1338	Serviceperson unintentionally vents refrigerant	0.001	Interviews with service center personnel indicated that leaks, although thought to be de minimis, would be possible during refrigerant transfer and disposal. We assume that 1/1000 of the leaks are more than de minimis.	Basic Event
Event1342	Friction spark (e.g., power tools) occurs	1	Interviews with service center personnel indicated that power tools are used all the time in conjunction with and around repair activities. Sparks are highly likely to occur in such an environment.	Basic Event
Event1340	Flammable refr. cloud spatially coincides w/spark source	0.0001	Interviews with service center personnel indicated that most of the leaks they address are pinhole leaks, which may not accumulate to a flammable concentration. The indoor spaces in which the repair work takes place are typically large, effectively equivalent to being outdoors, so whether servicing is indoors or outdoors the refrigerant would need to be released inside the trailer to have a reasonable probability of accumulating to a flammable concentration. A serviceperson working on the refrigeration system will have training in the use of flammable refrigerants and is unlikely to have both released the refrigerant in a confined area and then use a sparking power tool in the same confined area.	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1341	Flammable refr. cloud temporally coincides w/spark source	0.000002	Interviews with service center personnel indicated that most of the refrigerant release would be expected to occur from a trailer that arrives with an existing leak, prior to evacuation of the charge for servicing. Evacuation is typically the first step in servicing the refrigeration system, however, and would occur before other tools were used on the trailer. The leaks that are most likely to occur at the same time as a spark source (intentional or unintentional venting of refrigerant) both involve activity by the serviceperson, decreasing the likelihood that the flammable cloud persists until a spark source is introduced (see the lower probability of Events 1338 and 1530 relative to 1336). Only 1 in 500 leaks are the type caused by a serviceperson that have the potential to coincide with a spark source, and a factor of 1E-3 is applied to account for the fact that not all of these releases will persist long enough to coincide with a spark source.	Basic Event
Gate852	No ignition mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Event1344	Burning velocity not limiting	0.05	Refrigerants are stored under pressure or vacuum when evacuated and/or in servicing, so the release of refrigerant would be expected to generate some air currents. Additionally, many natural air circulation currents exceed the R-516A burning velocity of 4.75 cm/s. Burning velocity is likely to be a limiting factor in most (at least 95%) of encountered environments.	Basic Event
Event1349	Hot work occurs	1	Interviews with service center personnel indicated that welding/brazing work on the body/insulation is performed in the vicinity of refrigerant, which should be evacuated, on nearly all jobs. Soldering is common, but other hot work is typical for less than 50% of repair jobs.	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1350	Flammable refr. cloud spatially coincides w/hot surface	0.0001	Interviews with service center personnel indicated that most of the leaks they address are pinhole leaks, which may not accumulate to a flammable concentration. The indoor spaces in which the repair work takes place are typically large, effectively equivalent to being outdoors, so whether servicing is indoors or outdoors the refrigerant would need to be released inside the trailer to have a reasonable probability of accumulating to a flammable concentration. A serviceperson working on the refrigeration system will have training in the use of flammable refrigerants and is unlikely to have both released the refrigerant in a confined area and then perform welding/brazing in the same confined area.	Basic Event
Event1351	Flammable refr. cloud temporally coincides w/hot surface	0.000002	Interviews with service center personnel indicated that most of the refrigerant release would be expected to occur from a trailer that arrives with an existing leak, prior to evacuation of the charge for servicing. Evacuation is typically the first step in servicing the refrigeration system, however, and would occur before other tools were used on the trailer. The leaks that are most likely to occur at the same time as hot work (intentional or unintentional venting of refrigerant) both involve activity by the serviceperson, decreasing the likelihood that the flammable cloud persists until hot work is introduced (see the lower probability of Events 1338 and 1530 relative to 1336). Only 1 in 500 leaks are the type caused by a serviceperson that have the potential to coincide with hot work, and a factor of 1E-3 is applied to account for the fact that not all of these releases will persist long enough to coincide with a spark source.	Basic Event
Gate857	No ignition mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Event1361	Lighter/match used	0.00005	Interviews with service center personnel indicate that, in general, 10-50% of repair personnel may be smokers. Smoking is not allowed indoors, however, and repair personnel have training in that regard. Thus, a basic human error probability associated with failure to follow training (1E-4; Blackman et al., 2008) is multiplied by the upper bound estimates of personnel that smoke (50%).	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1362	Flammable refr. cloud spatially coincides w/flame	0.001	Interviews with service center personnel indicated that most of the leaks they address are pinhole leaks, which may not accumulate to a flammable concentration. The indoor spaces in which the repair work takes place are typically large, effectively equivalent to being outdoors, so whether servicing is indoors or outdoors the refrigerant would need to be released inside the trailer to have a reasonable probability of accumulating to a flammable concentration. A serviceperson working on the refrigeration system will have training in the use of flammable refrigerants and is unlikely to have both released the refrigerant in a confined area and then smoke in the same confined area. A serviceperson may decide to smoke prior to undertaking service work, however, so a pre-existing flammable concentration from a pinhole leak could be present. The probability of spatial coincidence was increased by an order of magnitude relative to the hot work and spark scenarios.	Basic Event
Event1363	Flammable refr. cloud temporally coincides w/flame	0.02	A match takes 5 seconds to strike and light a cigarette. A butane lighter would be similar. A cigarette takes about 5 minutes to smoke. Conservatively assuming one smoker is always smoking in the repair area, lighting events would occur 1/60 of the time.	Basic Event
Gate863	No ignition mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Event1364	Burning velocity not limiting	0.1	Refrigerants are stored under pressure or vacuum when evacuated and/or in servicing, so the release of refrigerant would be expected to generate some air currents. Additionally, many natural air circulation currents exceed the R-516A burning velocity of 4.75 cm/s. Burning velocity is likely to be a limiting factor in most (at least 95%) of encountered environments. If the ignition event were caused by lighter/match use prior to evacuating the refrigerant, however, air currents could be reduced, and the probability was increased to 0.1 (double the value used for the hot work and spark scenarios)	Basic Event
Gate848	No leak mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1366	Servicing other vehicle component occurs indoors	0.04	Interviews with service center personnel indicated that a substantial portion of repair work occurs outdoors. In this analysis, we assumed that 80% of the work occurs outdoors and 20% occurs indoors. The servicing work at the facilities was reported to be 20% non-refrigeration-related and 80% refrigeration-related. Thus, the probability of servicing the non-refrigeration system indoors is 20% * 20% = 0.04.	Basic Event
Event1369	Serviceperson unintentionally vents refrigerant	0.0001	For service personnel to release refrigerant when working on other components would constitute an accident for a trained professional, and the basic human error probability for a trained individual of 1E-4 (Blackman et al., 2008) is used. The risk of release during refrigerant transfer and disposal would not be applicable here.	Basic Event
Event1371	Flammable refr. cloud spatially coincides w/spark source	0.0001	Interviews with service center personnel indicated that most of the leaks they address are pinhole leaks, which may not accumulate to a flammable concentration. The indoor spaces in which the repair work takes place are typically large, effectively equivalent to being outdoors, so whether servicing is indoors or outdoors the refrigerant would need to be released inside the trailer to have a reasonable probability of accumulating to a flammable concentration. The risk of release during refrigerant transfer and disposal would not be applicable here, since the servicing is for non-refrigeration equipment. Leak checks are always performed before servicing. While flammable concentrations are less likely to be reached, personnel working on non-refrigeration equipment may not be trained for flammable refrigerant safety, and a value of 1E-4 (the same as for servicing the refrigeration system) is used.	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1372	Flammable refr. cloud temporally coincides w/spark source	0.000001	Interviews with service center personnel indicated that most of the refrigerant release would be expected to occur from a trailer that arrives with an existing leak. Leak checks are always performed before servicing. For flammable concentrations to be reached for servicing, the doors to the trailer must have generally remained closed, and the ignition source must become present quickly, before the refrigerant disperses. A factor of 0.01 is applied to the human error probability for someone with specialized training (1E-4; Blackman et al., 2008)	Basic Event
Gate877	No ignition mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Event1383	Burning velocity not limiting	0.1	Many natural air circulation currents exceed the R-516A burning velocity of 4.75 cm/s. Burning velocity is likely to be a limiting factor in most (at least 95%) of encountered environments. If the ignition event were caused by a serviceperson soon after entering the trailer, however, air currents could be reduced in some areas, and the probability was increased to 0.1	Basic Event
Event1373	Hot work occurs	1	Interviews with service center personnel indicated that welding/brazing work on the body/insulation is performed in the vicinity of refrigerant, which should be either evacuated or hermetically sealed, on nearly all jobs. Soldering is common, but other hot work is typical for less than 50% of repair jobs.	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1374	Flammable refr. cloud spatially coincides w/hot surface	0.0001	Interviews with service center personnel indicated that most of the leaks they address are pinhole leaks, which may not accumulate to a flammable concentration. The indoor spaces in which the repair work takes place are typically large, effectively equivalent to being outdoors, so whether servicing is indoors or outdoors the refrigerant would need to be released inside the trailer to have a reasonable probability of accumulating to a flammable concentration. The risk of release during refrigerant transfer and disposal would not be applicable here, since the servicing is for non-refrigeration equipment. Leak checks are always performed before servicing. While flammable concentrations are less likely to be reached, personnel working on non-refrigeration equipment may not be trained for flammable refrigerant safety, and a value of 1E-4 (the same as for servicing the refrigeration system) is used.	Basic Event
Event1375	Flammable refr. cloud temporally coincides w/hot surface	0.0000005	Interviews with service center personnel indicated that most of the refrigerant release would be expected to occur from a trailer that arrives with an existing leak. The risk of release during refrigerant transfer and disposal would not be applicable here, since the servicing is for non-refrigeration equipment. Leak checks are always performed before servicing. Hot work takes longer to initialize than the use of standard power tools, so the probability used for Event 1372 is halved.	Basic Event
Gate878	No ignition mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1380	Flammable refr. cloud spatially coincides w/flame	0.001	Interviews with service center personnel indicated that most of the leaks they address are pinhole leaks, which may not accumulate to a flammable concentration. The indoor spaces in which the repair work takes place are typically large, effectively equivalent to being outdoors, so whether servicing is indoors or outdoors the refrigerant would need to be released inside the trailer to have a reasonable probability of accumulating to a flammable concentration. A serviceperson may decide to smoke prior to undertaking service work, however, so a pre-existing flammable concentration from a pinhole leak could be present. The probability of spatial coincidence was increased by an order of magnitude relative to the hot work and spark scenarios.	Basic Event
Gate880	No ignition mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Gate867	No leak mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Event1391	Servicing refrigeration system occurs outdoors	0.64	Interviews with service center personnel indicated that a substantial portion of repair work occurs outdoors. In this analysis, we assumed that 80% of the work occurs outdoors and 20% occurs indoors. The servicing work at the facilities was reported to be 20% non-refrigeration-related and 80% refrigeration-related. Thus, the probability of servicing the refrigeration system outdoors is 80% * 80% = 0.64.	Basic Event
Gate908	No ignition mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Gate909	No ignition mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Event1408	Lighter/match used	0.5	Interviews with service center personnel indicate that, in general, 10-50% of repair personnel may be smokers. Smoking is permitted in outdoor areas at some service centers.	Basic Event
Gate911	No ignition mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Gate886	No leak mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1392	Servicing other vehicle component occurs outdoors	0.16	Interviews with service center personnel indicated that a substantial portion of repair work occurs outdoors. In this analysis, we assumed that 80% of the work occurs outdoors and 20% occurs indoors. The servicing work at the facilities was reported to be 20% non-refrigeration-related and 80% refrigeration-related. Thus, the probability of servicing the non-refrigeration system outdoors is 80% * 20% = 0.16.	Basic Event
Gate912	No ignition mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Gate913	No ignition mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Gate915	No ignition mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Gate889	No leak mitigation		Mitigation would be expected to be disabled during servicing	Remarks Gate
Event1091	Friction spark (e.g., dolly, box cutter) occurs	0.01	Friction sparks are expected to occur frequently during (un)loading of a refrigerated trailer from dolly activity and other interactions. Most sparks are in the range of 20-30 mJ (ACC, 2007), so it would require a very high energy spark to exceed the R-516A MIE of 81 mJ. Only 1% or less of sparks are expected to exceed this threshold.	Basic Event
Event1092	Broken internal component (e.g., lighting, thermostat) spark occurs	0.06	On-site surveys at refrigerated transport service centers reported damage during (un)loading as a common occurrence, with a frequency of about 1/8 that of routine maintenance visits. Routine maintenance occurs approximately once every two years (every 3000 operating hours). A frequency of 1/8 the routine maintenance value (1/16 per year) is used.	Basic Event
Event1082	Flammable refr. cloud spatially coincides w/spark source	1	CFD modeling shows that a refrigerant leak rapidly reaches flammable concentrations in a 3-compartment trailer, even before the refrigerant cloud reaches the door of the trailer (which would be open for (un)loading). While (un)loading activities could cause air currents that would disperse leaked refrigerant, a value of 1 was used to be conservative.	Basic Event

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Event1083	Flammable refr. cloud temporally coincides w/spark source	1	CFD modeling into a closed 3-compartment trailer shows that leaked refrigerant persists at flammable concentrations following a release. While an open door and (un)loading activities will decrease the time elevated concentrations are present, it is expected that concentrations will persist for many minutes, providing ample time to coincide with a spark source.	Basic Event
Event1085	Burning velocity not limiting	0.1	The low burning velocity of R-516A (4.75 cm/s) will be exceeded by many air currents generated as part of (un)loading activities and infiltration of outdoor air during (un)loading. A value 10% of the value used for burning velocity limitations during mobile transport is used.	Basic Event
Event1124	Person uses lighter/match in or near the trailer	0.51	Data from the CDC indicate that approximately 51% of long-haul truck drivers smoke (CDC, 2015).	Basic Event
Event1115	Flammable refr. cloud spatially coincides w/flame source	1	CFD modeling shows that a refrigerant leak rapidly reaches flammable concentrations in a 3-compartment trailer, even before the refrigerant cloud reaches the door of the trailer (which would be open for (un)loading). While (un)loading activities could cause air currents that would disperse leaked refrigerant, a value of 1 was used to be conservative.	Basic Event
Event1116	Flammable refr. cloud temporally coincides w/flame source	1	A cigarette takes about 5 minutes to smoke. CFD modeling shows that a refrigerant leak rapidly reaches flammable concentrations in a 3-compartment trailer, even before the refrigerant cloud reaches the door of the trailer (which would be open for (un)loading), and is expected to persist for more than 5 minutes. Assuming one smoker is always smoking in the vehicle while it is being (un)loaded, a lighting event will occur during the time a flammable concentration is present. While (un)loading activities could cause air currents that would disperse leaked refrigerant, a value of 1 was used to be conservative.	Basic Event
Gate715	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent someone from striking a match or igniting a lighter.	Remarks Gate
Gate739	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent someone from striking a match or igniting a lighter.	Remarks Gate

Table C.1 3-compartment trailer fault tree inputs

Identifier	Title	Input Value	Remarks	Type
Gate957	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent someone from striking a match or igniting a lighter.	Remarks Gate
Gate972	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent a windblown or external spark source.	Remarks Gate
Gate761	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent someone from striking a match or igniting a lighter.	Remarks Gate
Gate973	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent a windblown or external spark source.	Remarks Gate
Gate762	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent someone from striking a match or igniting a lighter.	Remarks Gate
Gate974	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent a windblown or external spark source.	Remarks Gate
Gate968	Automatic shutoff (electronics, compressor/pump) not present or fails		Automatic shutoffs would not prevent someone from striking a match or igniting a lighter.	Remarks Gate

Table C.2 3-compartment trailer fault tree inputs for other refrigerants

Identifier	Title	R-516A Input Value	R-454A Value	R-454A Remarks	R-455A Value	R-455A Remarks	R-1234yf Value	R-1234yf Remarks	R-290 Value	R-290 Remarks
Event1319	Vehicle accident causes damaged wire w/sufficient energy	1E-10	1E-11	Given the high MIE of R-454A, this value was decreased by a factor of 10.	1E-11	Given the high MIE of R-455A, this value was decreased by a factor of 10.	1E-13	Given the high MIE of R 1234yf, this value was decreased by a factor of 1000.	1E-07	Given the low MIE of R-290, this value was increased by a factor of 1000.
Event1325	Temperature, humidity do not prevent ignition	1	1	For R-454a, temperature and humidity are not expected to be limiting.	1	For R-455a, temperature and humidity are not expected to be limiting.	1	For R-1234yf, temperature and humidity are not expected to be limiting.	1	For R-290, temperature and humidity are not expected to be limiting.
Event1326	Broken internal component (e.g., lighting, thermostat) spark occurs	0.0003	5.3E-05	Given the high MIE of R-454A, a factor of 100 was applied to the frequency of spark occurrence from a broken internal component.	5.3E-05	Given the high MIE of R-455A, a factor of 100 was applied to the frequency of spark occurrence from a broken internal component.	5.3E-06	Given the high MIE of R 1234yf, a factor of 1000 was applied to the frequency of spark occurrence from a broken internal component.	5.3E-03	Given the low MIE of R-290, no factor was applied to the frequency of spark occurrence from a broken internal component.
Event1263	Friction spark (e.g., dolly, box cutter) occurs	0.01	1.0E-06	An extremely high energy friction spark would be required to ignite R-454A, which may be a one in a million occurrence.	1.0E-06	An extremely high energy friction spark would be required to ignite R-455A, which may be a one in a million occurrence.	0	Friction sparks are not expected to contain sufficient energy to ignite R-1234yf.	1	Many friction sparks are capable of igniting R-290.
Event1265	Burning velocity not limiting	0.06	0.06	The low burning velocity of R-454A similarly requires still air conditions.	0.06	The low burning velocity of R-455A similarly requires still air conditions.	0.06	The low burning velocity of R-1234yf similarly requires still air conditions.	1	Burning velocity is not frequently expected to be a limiting factor in R-290 ignition.

Table C.2 3-compartment trailer fault tree inputs for other refrigerants

Identifier	Title	R-516A Input Value	R-454A Value	R-454A Remarks	R-455A Value	R-455A Remarks	R-1234yf Value	R-1234yf Remarks	R-290 Value	R-290 Remarks
Event1535	Feed through plug fault occurs when flammable concentration is present	0.75	0.75	The flammable range span for R-454A is comparable to that of R-516A.	0.25	The flammable range for R-455A is narrow (11.8%-12.9%), and the probability of being in the correct range at the time of failure was lowered by a factor of 3.	0.75	The flammable range span for R-1234yf is comparable to that of R-516A.	0.75	The flammable range span for R-290 is comparable to that of R-516A.
Event1536	Release turbulence / wind does not prevent ignition	0.06	0.06	The low burning velocity of R-454A similarly requires still air conditions.	0.06	The low burning velocity of R-455A similarly requires still air conditions.	0.06	The low burning velocity of R-1234yf similarly requires still air conditions.	1	Burning velocity is not frequently expected to be a limiting factor in R-290 ignition.
Event1538	Flammable concentrations extend outside of condenser unit	0.01	0.005	The LFL for R-454A is higher than that of R-516A, so the probability was decreased by a factor of 2.	0.003	The LFL for R-455A is higher than that of R-516A, so the probability was decreased by a factor of 3.	0.01	The LFL for R-1234yf is comparable to that of R-516A.	0.03	The LFL for R-290 is lower than R-516A, so the probability was increased by a factor of 3.
Event1341	Flammable refr. cloud temporally coincides w/spark source	2E-06	1.0E-06	The LFL for R-454A is higher than that of R-516A, so the probability was decreased by a factor of 2.	6.7E-07	The LFL for R-455A is higher than that of R-516A, so the probability was decreased by a factor of 3.	2.0E-06	The LFL for R-1234yf is comparable to that of R-516A.	6.0E-06	The LFL for R-290 is lower than R-516A, so the probability was increased by a factor of 3.
Event1344	Burning velocity not limiting	0.05	0.05	Burning velocity is similarly likely to be a limiting factor in most (at least 95%) of encountered environments.	0.05	Burning velocity is similarly likely to be a limiting factor in most (at least 95%) of encountered environments.	0.05	Burning velocity is similarly likely to be a limiting factor in most (at least 95%) of encountered environments.	1	Burning velocity is not frequently expected to be a limiting factor in R-290 ignition.

Table C.2 3-compartment trailer fault tree inputs for other refrigerants

Identifier	Title	R-516A Input Value	R-454A Value	R-454A Remarks	R-455A Value	R-455A Remarks	R-1234yf Value	R-1234yf Remarks	R-290 Value	R-290 Remarks
Event1351	Flammable refr. cloud temporally coincides w/hot surface	2E-06	1.0E-06	The LFL for R-454A is higher than that of R-516A, so the probability was decreased by a factor of 2.	6.7E-07	The LFL for R-455A is higher than that of R-516A, so the probability was decreased by a factor of 3.	2.0E-06	The LFL for R-1234yf is comparable to that of R-516A.	6.0E-06	The LFL for R-290 is lower than R-516A, so the probability was increased by a factor of 3.
Event1364	Burning velocity not limiting	0.1	0.1	The burning velocity values were similarly doubled.	0.1	The burning velocity values were similarly doubled.	0.1	The burning velocity values were similarly doubled.	1	Burning velocity is not frequently expected to be a limiting factor in R-290 ignition.
Event1383	Burning velocity not limiting	0.1	0.1	The burning velocity values were similarly increased to 0.1.	0.1	The burning velocity values were similarly increased to 0.1.	0.1	The burning velocity values were similarly increased to 0.1.	1	Burning velocity is not frequently expected to be a limiting factor in R-290 ignition.
Event1091	Friction spark (e.g., dolly, box cutter) occurs	0.01	1.0E-06	An extremely high energy friction spark would be required to ignite R-454A, which may be a one in a million occurrence.	1.0E-06	An extremely high energy friction spark would be required to ignite R-455A, which may be a one in a million occurrence.	0	Friction sparks are not expected to contain sufficient energy to ignite R-1234yf.	1	Many friction sparks are capable of igniting R-290.
Event1085	Burning velocity not limiting	0.1	0.1	The burning velocity values were similarly set to 0.1.	0.1	The burning velocity values were similarly set to 0.1.	0.1	The burning velocity values were similarly set to 0.1.	1	Burning velocity is not frequently expected to be a limiting factor in R-290 ignition.