NAVIGANT

AHRI Project No. 8005:
Risk Assessment of Class 2L Refrigerants in Chiller Systems

Performance Analysis

Prepared for:

AHRI
AIR-CONDITIONING, HEATING,
& REFRIGERATION INSTITUTE

we make life better™

Prepared by:
Bill Goetzler
Matt Guernsey
Collin Weber

Navigant Consulting, Inc.
77 South Bedford St.
Suite 400
Burlington, MA 01803

781.270.0101
www.navigant.com

Final Report

July 2013

Disclaimer:

This material is based on current information and analysis that AHRI considers reliable, but AHRI does not represent it as accurate or complete, and it should not be relied on as such. Research report is a written or electronic communication that includes research analysis on the performance of low-GWP refrigerants in chillers. The information is provided merely informational and do not constitute an offer, solicitation for the purchase or sale of any products, inducement, promise, guarantee, warranty, or as an official confirmation of any transactions or contract of any kind.

Table of Contents

List of Figures and Tables

Figures:

Tables:

E. Executive Summary

As concerns about the global warming potential (GWP) of common fluorocarbon refrigerants have mounted in recent years, lower-GWP refrigerants have garnered increasing attention. Industry is now focusing on a new group of alternative refrigerants with low GWP, some of which are part of ASHRAE class 2L for flammability. Manufacturers of large equipment, such as chiller and refrigeration systems, have not begun using these refrigerants due to the flammability concerns of substantially larger amounts of refrigerant. AHRI has determined that a comprehensive performance assessment is needed to help the HVAC industry evaluate the feasibility of using various lower-GWP refrigerants in chiller systems.

E.1 Objective

The primary objective of this project is to assess the performance of lower-GWP alternative refrigerants in chillers. Specifically, we analyze the performance of R-744, R-32, R-717, R-290, R-1234yf, and R-1234ze(E), relative to baseline performance with R-410A or R-134a.

E.2 Approach

Our cycle performance analysis methodology followed the approaches outlined in the *ASHRAE Handbook – Fundamentals*, "Thermodynamics and Refrigeration Cycles." The model output the relevant state variables (e.g., suction pressure) at each point in the cycle, with the primary focus on the system coefficient of performance (COP). The team also evaluated two industry-accepted cycle enhancements: *economizers* for screw chillers and *work recovery expansion* for R744 systems.

E.3 Findings

Using compressor and motor efficiencies that are representative of current practices, the analyses calculated the performance of multiple system types.

In scroll compressor chiller applications, the key findings include:

- Both R-717 and R-290 produced higher theoretical COPs than baseline R-410A; however, higher flammability and/or toxicity impose costs and additional considerations.
- R-717's theoretical COP is the highest of any refrigerant studied. However, its high discharge temperatures and tendency to corrode copper require special designs.
- The A2L refrigerant, R-32, has a slightly higher COP (2-4%) than the baseline.
- The performance of R-744 was inferior to that of all other refrigerants, including the baseline. Calculations were consistent with results from literature.[1]

In screw chiller applications we found that all the alternative refrigerants analyzed (R-717, R-290, R-1234yf, and R-1234ze(E)) have COPs within 1-4% of the baseline, R-134a.

---

[1] Robinson & Groll, 1996

1. Introduction

1.1 Background

As concerns about the global warming potential (GWP) of common fluorocarbon refrigerants have mounted in recent years, lower-GWP refrigerants have garnered increasing attention. A number of lower-GWP alternative refrigerants including hydrofluoroolefins (HFOs) and blends are being evaluated as alternatives to higher GWP HFCs such as R-134a. Industry and government leaders, most likely using lifecycle climate change performance (LCCP) or total equivalent warming impact (TEWI) as a key criterion, will determine whether a transition away from higher GWP HFCs is desirable

Among the lower-GWP options being evaluated are hydrocarbons like R-290 (propane) and R-600a (isobutane), R-744 (carbon dioxide), and newly developed refrigerants like HFOs. Although efficient, hydrocarbons are highly flammable and present safety hazards to building occupants and service technicians. R-744 and R-717 are the best options with regards to direct global warming potential and flammability. However, the current technology required to use R-744 at a large scale is cost-prohibitive and R-717 has flammability and toxicity issues. Consequently, industry is seeking other alternative refrigerants which have low flammability, as well as lower GWP, combined with good thermodynamic efficiency.

Industry is focusing on a new group of alternative refrigerants with low GWP that ASHRAE classifies as 2L for flammability.[2] R-32 and R-1234yf are two of the 2L refrigerant options that industry is considering. Manufacturers of large equipment, such as chiller and refrigeration systems, have not begun using 2L refrigerants due to the concern of substantially larger amounts of refrigerant and concerns that standards and regulations have not yet been updated. AHRI has determined that a comprehensive performance is needed to help the HVAC industry evaluate the feasibility of using various lower-GWP refrigerants in chiller systems.

1.2 Objective

The primary objective of this project is to assess the performance associated with the use of lower-GWP alternative refrigerants in chillers. Specifically, we analyze the performance of R-744, R-32, R-717, R-290, R-1234yf, and R-1234ze(E), relative to baseline performance with R-410A or R-134a.

We worked cooperatively with AHRI members to leverage their experience during this study. The AHRI project monitoring subcommittee (PMS) was the primary conduit to these members.

---

[2] Based on the definition of refrigerant classes in ISO-817 standard. The flammability classification uses the numbers 1, 2, and 3, where class 1 has “no flame propagation,” class 2 has “lower flammability,” and class 3 has “higher flammability.” Class 2L is a specific subclass of class 2, and has lower flammability than the other class 2 refrigerants based on the burning velocity.

2. Performance Analyses

2.1 *Analysis Scenarios*

The team conducted thermodynamic cycle analyses to compare the performance of baseline and alternative refrigerants in each of five different chiller configurations. We selected chiller types and refrigerants for examination based on the project's statement of work (SOW); the AHRI PMS concurred with the chosen operating conditions and assumptions. Where applicable, the team considered potential cycle improvements, as Section 2.2 describes in detail. This approach allowed for a direct comparison of theoretical system performance of chillers with different refrigerants. Table 2-1 shows the scenarios and refrigerants analyzed in this work.

Table 2-1. Chiller Scenarios Analyzed

Compressor Type/Size:	100-Ton Air-Cooled Scroll	100-Ton Water-Cooled Scroll	200-Ton Air-Cooled Screw	200-Ton Water-Cooled Screw	400-Ton Water-Cooled Screw
Conventional Refrigerant:	**R-410A Baseline**		**R-134a Baseline**		
Alternative Refrigerants:	R-32 R-717 (Ammonia) R-290 (Propane) R-744 (CO_2)		R-717 (Ammonia) R-290 (Propane) R-1234yf R-1234ze(E)		

2.2 *Analysis Methodology*

For each of the five chiller types specified in Table 2-1, the team performed a simple cycle analysis to yield the following outputs:

- Theoretical coefficient of performance (COP)
- Compressor suction flow rate
- Suction pressure
- Discharge pressure
- Discharge temperature

We based our analysis of chiller performance on system specifications provided by the PMS, including the operating temperature conditions specified in Table 2-2.

Table 2-2. Chiller Operating Temperature Conditions

Chiller Type	Evaporating Temperature (°F)	Condensing Temperature (°F)	Subcooling (°F)	Superheat (°F)
Water-Cooled	40	100	8	0
Water-Cooled with Heat Recovery	40	115	8	0
Air-Cooled	38	125	20	8

Table 2-3 shows the compressor isentropic efficiency and motor efficiency provided by the PMS for each of the five chiller types. These compressor and motor efficiencies are representative of current practices. Note that the compressor isentropic efficiency values account for both the efficiency of the compression device itself and the efficiency of the motor used to drive the compressor. The motor efficiency values are shown separately here because they are used independently in the calculations for R-744 units featuring work recovery expansion. However, these motor efficiencies are the same values already accounted for in the compressor isentropic efficiencies.

Table 2-3. Compressor and Motor Efficiency Values

Chiller Type	Compressor Isentropic Efficiency (%)	Motor Efficiency (%)
400-ton water-cooled screw	74.0	95
200-ton water-cooled screw	73.0	95
100-ton water-cooled scroll	74.0	90
200-ton air-cooled screw	72.5	95
100-ton air-cooled scroll	74.0	90

Our cycle performance analysis methodology is consistent with the approaches outlined in detail in Chapter 2 of *ASHRAE Handbook – Fundamentals*, "Thermodynamics and Refrigeration Cycles." The team developed a model in Microsoft® Excel, utilizing the National Institute of Standards and Technology (NIST) Reference Fluid Thermodynamic and Transport Properties Database (REFPROP 9.0) as the source for fluid property information. The model evaluated the relevant state variables at each point in the cycle. The final outputs of the model included the aforementioned system COP, compressor suction flow rate, suction pressure, discharge pressure, and discharge temperature, as requested in the statement of work.

Systems using transcritical R-744 as the working fluid required one additional analysis step. In traditional vapor-compression refrigeration systems, the condensing pressure ("high-side pressure") can be calculated directly as a function of the known condensing temperature ("heat rejection temperature") and the properties of the fluid. This is the pressure at which the gas exiting the compressor will condense into liquid inside the heat exchanger under the given conditions. However, in the case of transcritical R-744 systems, where the fluid exists in a supercritical state inside the gas cooler, the system can function across a range of high-side pressures. Within this range, the system designer can vary the high-side pressure to obtain an optimal COP based on the system parameters and operating conditions. In our analysis of the transcritical R-744 chillers we iterated on high-side pressure in the Excel model, running the cycle analysis with increasing high-side pressures until the COP began to decrease We assumed the maximum COP (inflexion point) to be the optimized system performance under the given conditions.

The team also included cycle improvements for certain chillers, where applicable. These improvements are industry-accepted features that would typically be specified for equipment of the given type. We considered two improvements: *economizers* for screw chillers and *work recovery expansion* for R-744 systems. Both of these improvements increase the performance of the respective systems and are proven technologies, so we included them in the modeling of all systems of these two types.

Screw Compressor Economizing – We modeled economizing using a flash tank that receives the output of the condenser. The condenser output passes through a valve to a tank pressure that we assumed to be the geometric mean of the high and low-side pressures. The flash tank allows any vapor generated at this point to be separated out rather than being passed through the expansion valve and into the evaporator. The vapor collected in the flash tank is injected into the compressor at this intermediate pressure, where it is then fully compressed and discharged to the condenser. The result is improved heat absorption capacity at the evaporator, and thus increased system COP.

Work Recovery Expansion – We modeled a work recovery expansion device for all systems utilizing transcritical R-744 as the working fluid. In transcritical R-744 cycles, a major source of lost energy is the throttling that occurs between the gas cooler and the evaporator, between which exists a pressure differential of hundreds of pounds per square inch. The work recovery device serves to convert some of these throttling losses into useful work, which can be fed back into the system. We conducted a literature search to enable estimation of the efficacy of an expander that manufacturers could realistically implement in future chillers. Based on the literature review, discussion with researchers, and confirmation of the PMS, we modeled the work recovery expansion device as having an isentropic efficiency of 65%. We calculated the recovered work based on the properties of the gas cooler and evaporator, and fed that work into the compressor model, reducing the electrical energy needed by the compressor and thus increasing the system COP.

2.3 *Analysis Findings and Conclusions*

The team calculated analytical results for each of the scenarios shown in Table 2-1, above. The analyses yielded insights into the performance of alternative refrigerants. Figure 2-1, Figure 2-2, and Figure 2-3 compare the COP values obtained for each combination of chiller configuration and refrigerant analyzed, each figure dedicated to a specific chiller size and type. Section 3 provides full analytical results.

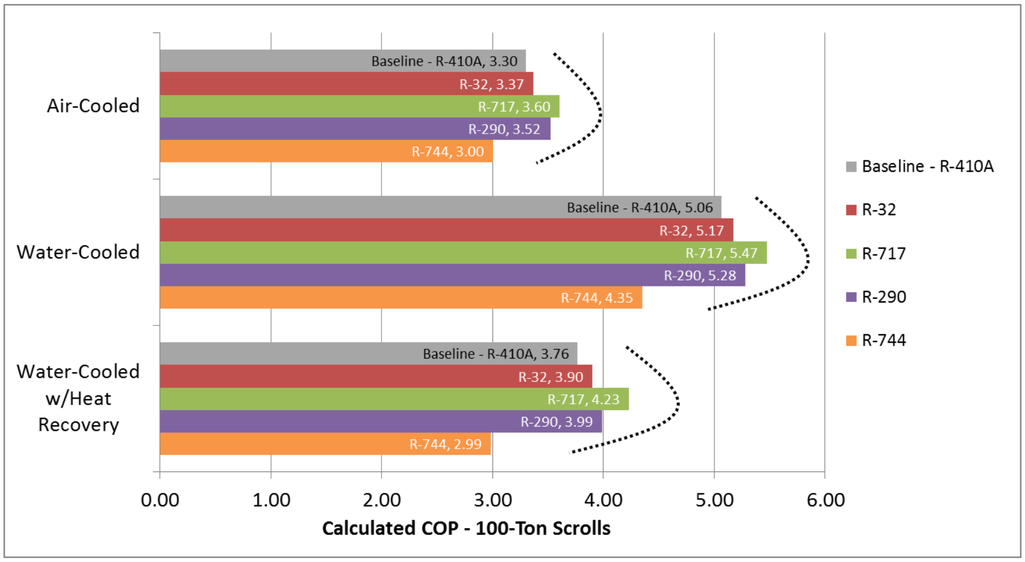


Figure 2-1. COP Values for 100-Ton Scroll Chillers

In scroll chiller applications, we found the following:

- Both R-717 and R-290 produced higher theoretical COPs (by 8-12% and 4-6%, respectively) than baseline R-410A. Note that higher flammability and/or toxicity impose practical limitations.
- R-717's theoretical COP is the highest of any refrigerant studied. However, its high discharge temperatures (up to 300 °F in the analysis results) and tendency to corrode copper would require special design considerations if used in scroll compressors.
- The A2L refrigerant, R-32, has a slightly higher COP (2-4%) than the baseline.
- The performance of R-744 was inferior to that of all other refrigerants, including the baseline. Calculations were consistent with results from literature.[3]

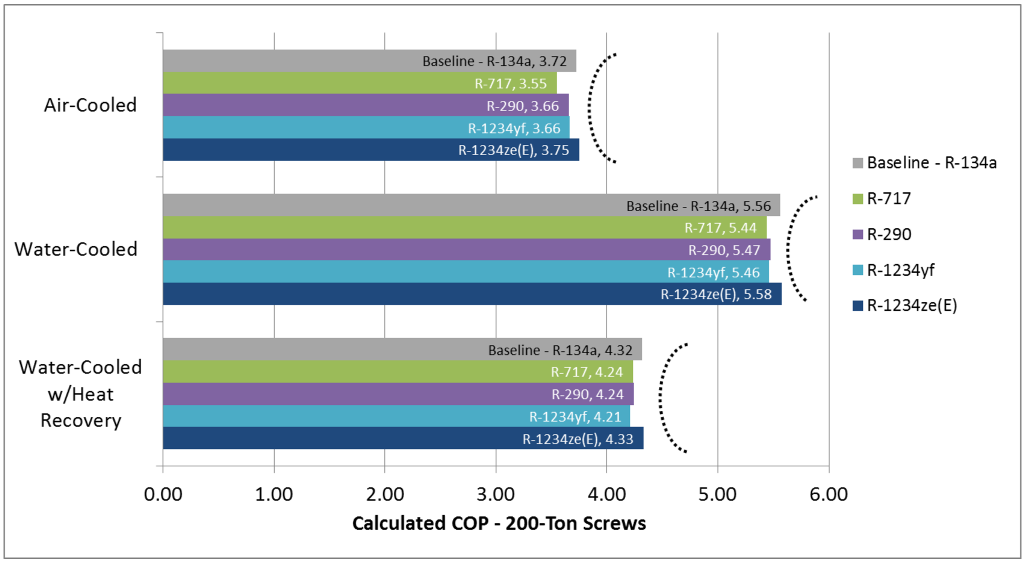


Figure 2-2. COP Values for 200-Ton Screw Chillers

---

[3] Robinson & Groll, 1996

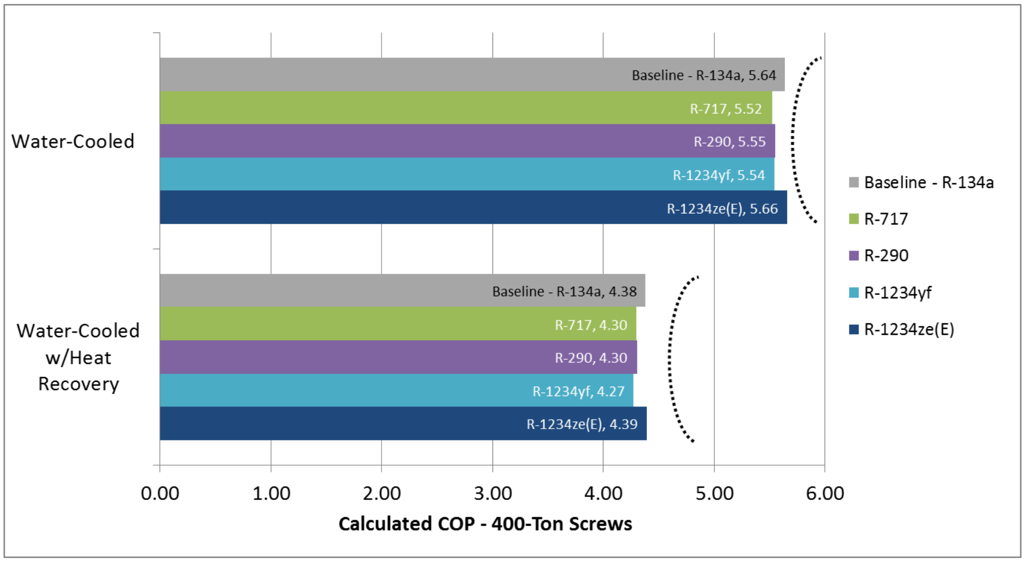


Figure 2-3. COP Values for 400-Ton Screw Chillers

In screw chiller applications we found that all the alternative refrigerants analyzed (R-717, R-290, R-1234yf, and R-1234ze(E)) have COPs within 1-4% of the values calculated for the baseline, R-134a.

This study focused solely on a theoretical simple cycle analysis, with fixed conditions and inputs, to produce estimates of performance potential that could be compared across refrigerants. Further investigation of the performance potential of these refrigerants would require in-depth analysis based upon individual system designs, applications, desired operating characteristics, and heat transfer characteristics in evaporators and condensers.

3. Full Analytical Results

The team conducted simulation and modeling of the performance of the different chiller scenarios presented in the project statement of work. We performed simple thermodynamic cycle analysis for each scenario utilizing a Microsoft Excel spreadsheet for computations and NIST REFPROP 9.0 software as the source for fluid property information. These analyses utilize the compressor and motor efficiencies outlined in Table 2-3, above. For each of the eight total scenarios, we calculated requested cycle properties, including theoretical COP, compressor suction flow rate, suction pressure, discharge pressure, and discharge temperature. Table 3-1 through Table 3-8 show the complete results of the cycle modeling. The first column of data contains the baseline refrigerant case for the given equipment setup.

Table 3-1: Analytical performance results for 100-ton air-cooled scroll chillers

Refrigerant	Base: R-410A	R-32	R-717	R-290	R-744
Theoretical COP	**3.30**	**3.37**	**3.60**	**3.52**	**3.00**
Compressor suction flow rate (CFM/RT)	**1.41**	1.27	1.81	2.41	0.58
Suction pressure (psia)	**129**	131	70	76	552
Discharge pressure (psia)	**462**	473	308	258	1409
Discharge temperature (F)	**186**	224	301	157	187

Table 3-2: Analytical performance results for 200-ton air-cooled screw chillers

Refrigerant	Base: R-134a	R-717	R-290	R-1234yf	R-1234ze(E)
Theoretical COP	**3.72**	**3.55**	**3.66**	**3.66**	**3.75**
Compressor suction flow rate (CFM/RT)	**2.78**	1.69	2.09	2.86	3.70
Suction pressure (psia)	**48**	70	76	51	35
Discharge pressure (psia)	**199**	308	258	197	151
Discharge temperature (F)	**158**	304	156	139	144

Table 3-3: Analytical performance results for 100-ton water-cooled scroll chillers

Refrigerant	Base: R-410A	R-32	R-717	R-290	R-744
Theoretical COP	**5.06**	**5.17**	**5.47**	**5.28**	**4.35**
Compressor suction flow rate (CFM/RT)	**1.25**	1.15	1.66	2.17	0.52
Suction pressure (psia)	**133**	136	73	79	568
Discharge pressure (psia)	**332**	340	212	189	1169
Discharge temperature (F)	**138**	162	213	119	144

Table 3-4: Analytical performance results for 100-ton water-cooled scroll chillers with heat recovery

Refrigerant	Base: R-410A	R-32	R-717	R-290	R-744
Theoretical COP	**3.76**	**3.90**	**4.23**	**3.99**	**2.99**
Compressor suction flow rate (CFM/RT)	**1.38**	1.23	1.73	2.36	0.57
Suction pressure (psia)	**133**	136	73	79	568
Discharge pressure (psia)	**406**	416	266	228	1455
Discharge temperature (F)	**161**	192	255	137	178

Table 3-5: Analytical performance results for 200-ton water-cooled screw chillers

Refrigerant	Base: R-134a	R-717	R-290	R-1234yf	R-1234ze(E)
Theoretical COP	**5.56**	**5.44**	**5.47**	**5.46**	**5.58**
Compressor suction flow rate (CFM/RT)	**2.55**	1.57	1.93	2.62	3.40
Suction pressure (psia)	**50**	73	79	53	37
Discharge pressure (psia)	**139**	212	189	140	105
Discharge temperature (F)	**119**	214	119	106	110

Table 3-6: Analytical performance results for 200-ton water-cooled screw chillers with heat recovery

Refrigerant	Base: R-134a	R-717	R-290	R-1234yf	R-1234ze(E)
Theoretical COP	**4.32**	**4.24**	**4.24**	**4.21**	**4.33**
Compressor suction flow rate (CFM/RT)	**2.63**	1.60	1.99	2.72	3.51
Suction pressure (psia)	**50**	73	79	53	37
Discharge pressure (psia)	**173**	266	228	172	131
Discharge temperature (F)	**137**	256	136	122	126

Table 3-7: Analytical performance results for 400-ton water-cooled screw chillers

Refrigerant	Base: R-134a	R-717	R-290	R-1234yf	R-1234ze(E)
Theoretical COP	**5.64**	**5.52**	**5.55**	**5.54**	**5.66**
Compressor suction flow rate (CFM/RT)	**2.55**	1.57	1.93	2.62	3.40
Suction pressure (psia)	**50**	73	79	53	37
Discharge pressure (psia)	**139**	212	189	140	105
Discharge temperature (F)	**118**	212	118	105	109

Table 3-8: Analytical performance results for 400-ton water-cooled screw chillers with heat recovery

Refrigerant	Base: R-134a	R-717	R-290	R-1234yf	R-1234ze(E)
Theoretical COP	**4.38**	**4.30**	**4.30**	**4.27**	**4.39**
Compressor suction flow rate (CFM/RT)	**2.63**	1.60	1.99	2.72	3.51
Suction pressure (psia)	**50**	73	79	53	37
Discharge pressure (psia)	**173**	266	228	172	131
Discharge temperature (F)	**136**	253	136	121	125

NAVIGANT

AHRI Project No. 8005:

Risk Assessment of Class 2L Refrigerants in Chiller Systems

Prepared for:

AHRI

AIR-CONDITIONING, HEATING,
& REFRIGERATION INSTITUTE

we make life better™

Prepared by:
Bill Goetzler
Matt Guernsey
Collin Weber

Navigant Consulting, Inc.
77 South Bedford St.
Suite 400
Burlington, MA 01803

781.270.0101
www.navigant.com

Final Report
July 2013

Disclaimer:

This material is based on current information and analysis that AHRI considers reliable, but AHRI does not represent it as accurate or complete, and it should not be relied on as such. Research report is a written or electronic communication that includes research analysis on the performance of low-GWP refrigerants in chillers. The information is provided merely informational and do not constitute an offer, solicitation for the purchase or sale of any products, inducement, promise, guarantee, warranty, or as an official confirmation of any transactions or contract of any kind.

Table of Contents

List of Figures and Tables

Figures:

Tables:

E. Executive Summary

As concerns about the global warming potential (GWP) of common fluorocarbon refrigerants have mounted in recent years, lower-GWP refrigerants have garnered increasing attention. Industry is now focusing on a new group of alternative refrigerants with low GWP, some of which are flammable and classified as 2L (ASHRAE 34). Manufacturers of large equipment, such as chiller and refrigeration systems, have not begun using these refrigerants due to the flammability concerns of substantially larger amounts of refrigerant. AHRI has determined that a comprehensive risk assessment is needed to help the HVAC industry evaluate the feasibility of using Class 2L refrigerants in chiller systems.

E.1 Objective

The primary objective of this project is to assess the safety risks associated with the use of Class 2L refrigerants in chillers. Specifically, we investigate the risks of using refrigerants such as R-32, R-1234yf, or R-1234ze(E) during operation, servicing, and installation/commissioning in both water-cooled and air-cooled chillers. A fault tree analysis forms the basis for this risk assessment.

E.2 Approach

The Fault Tree Analysis (FTA) followed these steps:

1. Define the system and activities
2. Characterize the leak scenarios and build fault trees
3. Estimate frequency of each hazard scenario
4. Calculate overall risks
5. Compare to other known risk levels
6. Evaluate mitigation strategies

FTA is an approach to failure/risk analysis which uses boolean logic to combine individual events that may lead to a specific system failure. Fault trees are built on the risks or likelihood of failure of various components in the system. Each individual component is connected in the tree depending on whether a failure of one component or all components is required for a system or subsystem to fail. To calculate predicted risk of the system, we use Monte Carlo simulation to randomly simulate failure of individual events. The system failure risk is calculated as the number of top level event failures out of the total number of simulations, i.e., the predicted risk of refrigerant ignition for given system.

The basic structure of the fault tree contains four primary branches, one for each unique operating state: installation/commissioning (i.e., startup), sitting after installation (prior to initiation of normal operation), servicing, and normal operation. This analysis does not cover manufacturing and transportation risk, as they are outside of the scope of this study. When combining the individual risk associated with each of the four primary branches, we weighted each branch by the expected annual duration for each operating state.

Within each branch, we evaluate total predicted risk based on the likelihood of a refrigerant leak that is sufficiently large to create a flammable concentration and the likelihood of an active ignition source being present. We identified potential ignition sources and the probability of occurrence for each one through literature review and interviews with chiller technicians and other industry experts.

Manufacturers provided the leak frequency data used in each of five different scenarios. Table 1 describes each scenario.

Table 1. Risk Scenarios

Scenario	Chiller*	Location	Description
A	400T WC Screw	Mechanical Room	ASHRAE-code-compliant mechanical room, as found in typical large commercial buildings. Two identical chillers are located in the room.
B	200T AC Screw	Rooftop	Units that have free-flowing air that is not hindered by wind/sound screens or walls of adjacent buildings.
C	100T AC Scroll		
D	200T AC Screw	Rooftop w/ restricted airflow	Units that are located in pits, or have wind/sound-screens that may inhibit airflow and induce stagnation of refrigerant vapors.
E	100T AC Scroll		

Note: WC = Water Cooled, AC = Air Cooled
*Each chiller operates with a single circuit

E.3 Findings

Figure 1 shows the risk of ignition for each of the five scenarios under each of four operating states: normal operations, servicing, installation and commissioning, and sitting post-installation. For the indoor scenario (A), the predicted risk for normal operations is split to distinguish the risk when ventilation is running from when ventilation is off. This distinction is not relevant for the other scenarios since they are all located outdoors. The total risk is an average of the risk in each operating state, weighted by the time per year in each state.

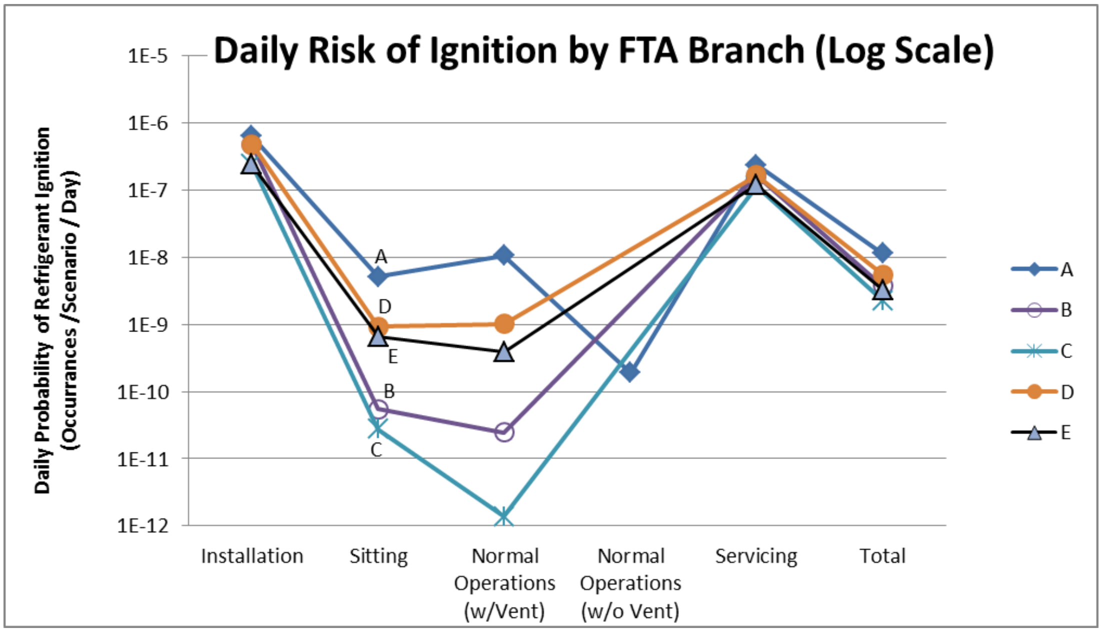


Figure 1. Comprehensive Fault Tree Analysis Results for Daily Risk by Scenario

Table 2 shows the total annual risk for each of the five scenarios. These data are the probabilities for refrigerant ignition per year in each scenario.

Table 2. Total Annual Risk of Ignition for Chiller Scenarios

	Scenario	Chiller	Location	Annual Risk of Ignition*
Increasing Risk →	**A**	Single-Circuit 400T WC Screw (2x)	Mechanical Room	4.2 E-6
	D	200T AC Screw	Rooftop (restricted airflow)	2.0 E-6
	B	200T AC Screw	Rooftop (unrestricted airflow)	1.4 E-6
	E	100T AC Scroll	Rooftop (restricted airflow)	1.2 E-6
	C	100T AC Scroll	Rooftop (unrestricted airflow)	8.3 E-7

* Units for Risk are occurrences (refrigerant ignitions) per scenario per year

The key findings include:

- **Daily risk**: For all scenarios, service and installation activities are predicted to present the highest risk on any given day, due to the added presence of ignition sources associated with technicians.
- **Annual risk:** The normal operations risk constitutes a majority of the total risk since the normal operating state prevails for 98% of the year. However, as expected, the smaller the predicted risk for normal operations, the smaller the impact that risk played as a portion of the total predicted risk. This is particularly relevant for Scenarios B and C, which had predicted risk that was one and two orders of magnitude less than the other scenarios, respectively.
- **Indoor vs. outdoor** – The rooftop/outdoor scenarios exhibited lower predicted risk than the mechanical room scenario due to both the lack of potential ignition sources in close proximity (and inaccessibility by people in most cases), as well as the inability to form flammable concentrations due to rapid refrigerant dispersion.
- **Restricting airflow** – By comparing results of Scenario B to D, and Scenario C to E, we find that restricting airflow to these outdoor chillers is predicted to have minimal impact on risk. Even with restricted airflow, the charges involved do not produce a long-lasting flammable concentration.
- **Charge size:** the predicted risk in outdoor chillers will only increase minimally with an increase in charge size (i.e., capacity), whereas the predicted risk for an indoor installation is directly proportional to the amount of refrigerant in the chiller. This is due to the fact that outdoors a flammable concentration will not build up and the risk is due primarily to technician or contractor error or someone who brings an ignition source into contact with a leaking jet of refrigerant. Indoors, a flammable concentration can build up if not detected, which could be ignited by an otherwise safe ignition source across the room. The larger the charge, the faster the concentration can reach the LFL, and the longer the vapor will linger.
- **Ventilation and leak detection** – An increase in the likelihood of chiller self-diagnosis (i.e., greater likelihood of the chiller or building management system identifying a leak) or an increase in refrigerant monitor reliability (i.e., lower likelihood of monitor failure) by approximately 75% reduces total risk by 53%. An increase in reliability of both variables together reduces total risk by 62%. Improving reliability of safety systems and ensuring that precautions

can be taken in the event of a leak are key drivers in the predicted risk of a system. Increased self-diagnosis capabilities may provide important assurances of reduced risk.

- **Number of chillers in a mechanical room** – Adding one additional chiller to the baseline (two identical chillers) increases the risk by approximately 47%, while removing one chiller from the baseline, so that only one is present, reduces the risk by 42%. Without additional detailed analysis of chiller sizes, it is unclear from this study whether the predicted risk would be lower to achieve the same cooling capacity using a single large chiller versus two smaller chillers.
- **Percentage of leaks that are large –** Results show that for a doubling in the percentage of leaks that are large (to 10% of all leaks), the total predicted risk increases by 73%. Interpolating the data shows that if approximately 13% of leaks are large, the predicted risk of ignition doubles. Additional understanding into the nature of refrigerant leaks, including frequency, total loss, and rate of loss would help refine predicted risk results.

1. Introduction

1.1 Background

As concerns about the global warming potential (GWP) of common fluorocarbon refrigerants have mounted in recent years, lower-GWP refrigerants have garnered increasing attention. A number of lower-GWP alternative refrigerants including hydrofluoroolefins (HFOs) and blends are being evaluated as alternatives to higher GWP HFCs such as R-134a. Industry and government leaders, most likely using lifecycle climate change performance (LCCP) or total equivalent warming impact (TEWI) as a key criterion, will determine whether a transition away from higher GWP HFCs is desirable

Among the lower-GWP options being evaluated are hydrocarbons like R-290 (propane) and R-600a (isobutane), and newly developed refrigerants like HFOs. Although efficient, hydrocarbons are highly flammable and present safety hazards to building occupants and service technicians. R-717 is the best option with regards to direct global warming potential and flammability. However, R-717 has flammability and toxicity issues. Consequently, industry is seeking other alternative refrigerants which have low flammability, as well as lower GWP, combined with good thermodynamic efficiency.

Industry is focusing on a new group of alternative refrigerants with low GWP that ASHRAE classifies as 2L for flammability.[1] R-32 and R-1234yf are two of the 2L refrigerant options that industry is considering. Manufacturers of large equipment, such as chiller and refrigeration systems, have not begun using 2L refrigerants due to the concern of substantially larger amounts of refrigerant and because standards and regulations have not been updated to account for such concerns. AHRI has determined that a comprehensive performance and risk assessment is needed to help the HVAC industry evaluate the feasibility of using various lower-GWP refrigerants in chiller systems and to help in the development of standards and codes.

1.2 Objective

The primary objectives of this project are to assess the safety risks associated with the use of lower-GWP alternative refrigerants in chillers. Specifically, we investigate risks of using A2L refrigerants such as R-32, R-1234yf, or R-1234ze(E) during operation, servicing, and installation/commissioning in both water-cooled and air-cooled chillers.[2] A fault tree analysis forms the basis for this risk assessment.

We worked cooperatively with AHRI members to leverage their experience during this study. The AHRI project monitoring subcommittee (PMS) was the primary conduit to these members.

---

[1] Based on the definition of refrigerant classes in the ASHRAE 34 standard. The flammability classification uses the numbers 1, 2, and 3, where class 1 has “no flame propagation,” class 2 has “lower flammability,” and class 3 has “higher flammability.” Class 2L is a specific subclass of class 2, and has lower flammability than the other class 2 refrigerants based on the burning velocity.

[2] A2L refrigerants are 2L refrigerants with lower toxicity. Higher-toxicity 2L refrigerants are in group B2L.

2. Risk Assessment Background

2.1 Summary

The risk assessment aimed to identify the risk of refrigerant vapor ignition in the event of a 2L refrigerant leak from a chiller. Per AHRI PMS guidance, Navigant only evaluated the likelihood of an ignition event (excluding the severity or consequences of such an event). We did not evaluate the risks of a fire due to refrigerant ignition, which includes additional, highly variable factors such as the amount of flammable material in close proximity to the chiller and ignition source, as well as the room layout and building materials.

The team selected R-32 as representative of the 2L refrigerants. In comparison to R-1234yf, R-32's Minimum Ignition Energy (MIE) is more than two orders of magnitude lower, but R-32's burning velocity (BV) is more than four times faster. However, R-32 does have a lower flammability limit (LFL), more than two times higher than R-1234yf, which reduces the risk of ignition. This analysis assumes that the greater ignition risk due to lower MIE more than balances the reduced risk from the higher LFL, and therefore MIE is the primary driver for likelihood of flammability.

Table 2-1 shows the flammability characteristics of the refrigerants of interest in this study.

Table 2-1. Common Refrigerant Flammability Characteristics[3]

Refrigerant	Class*	LFL (%v/v)	UFL (%v/v)	MIE (mJ)	BV (cm/s)	AIT (°F)
Direction of Lower Risk for Variable	NA	Higher	Lower	Higher	Lower	Higher
R-290 (Propane)	A3	2.5	10	0.25	46	1004
R-32	**A2L**	**14.4**	**29.3**	**30**	**6.7**	**1198**
R-1234yf	A2L	6.2	12.3	5,000	1.5	761
R-1234ze(E)	A2L	7.0	9.5	61,000		694
R-717 (Ammonia)	B2L	15	18	100	7.2	1204

*By definition, 2L refrigerants are those in Class 2 that have a burning velocity less than 10 cm/s

Note: LFL = lower flammability limit, UFL = upper flammability limit, MIE = minimum ignition energy, AIT = Auto-ignition temperature, BV = burning velocity.

Figure 2-1 shows the process by which we conducted the fault tree analysis (FTA), including the gathering of input data. The first portion of the process involved conducting research, then vetting the inputs and variables with industry experts, including the PMS, to confirm our results.

---

[3] Denis Clodic, "*Low GWP Refrigerants and Flammability Classification,*" Mines ParisTech, Table 2, p.6, available at: http://www.nedo.go.jp/content/100080128.pdf

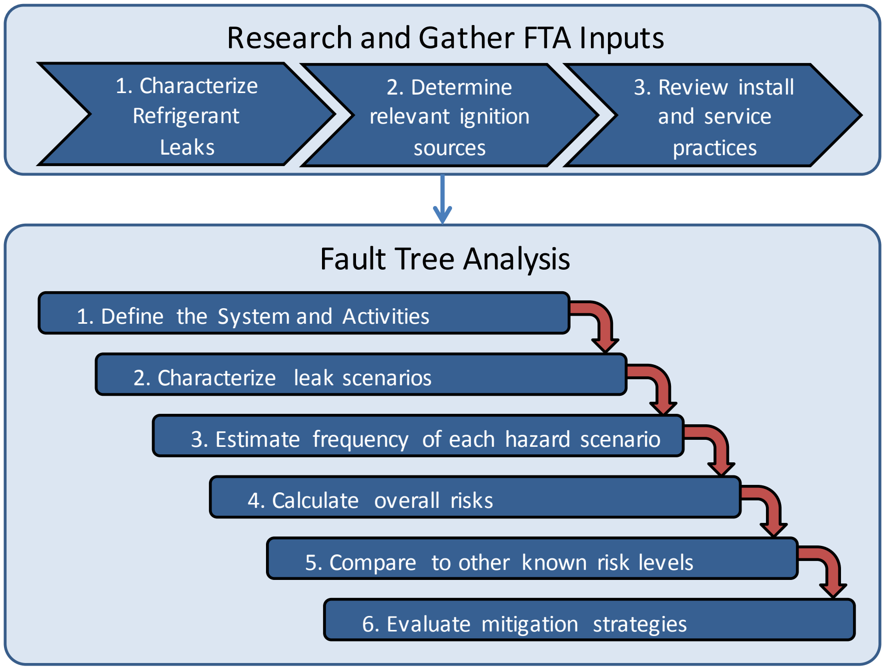


Figure 2-1. Fault Tree Analysis Development Methodology

To research and gather FTA inputs on the specific scenarios under evaluation (defined in Section 2.2), Navigant coordinated with PMS-member organizations via phone discussions and visits with local technicians, service managers, and building engineers. Interviews with technicians, particularly during on-site visits, provided valuable information on risk scenarios that drove both the nature of the inputs and the structure of the fault trees. To gather additional data we sent brief surveys to manufacturers that were not visited, for completion by technicians.

2.2 *Scenarios*

Table 2-2 shows the five scenarios for fault tree analysis defined for this project, in coordination with the PMS. Each scenario represents a unique risk situation. Note that, per PMS instruction, the risk in scenario A (400T WC Screw in a mechanical room) is based on the use of two identical chillers within a single mechanical room; all other scenarios represent the risk for a single chiller.

Table 2-2. Risk Scenarios

Scenario	Chiller Type	Location	Description
A	400T WC Screw	Mechanical Room	ASHRAE-code-compliant mechanical room, as found in typical large commercial buildings. Two identical chillers are located in the room.
B	200T AC Screw	Rooftop	Units that have free-flowing air that is not hindered by wind/sound screens or walls of adjacent buildings.
C	100T AC Scroll		
D	200T AC Screw	Rooftop w/ restricted airflow	Units that are located in pits, or have wind/sound-screens that may inhibit airflow and induce stagnation of refrigerant vapors.
E	100T AC Scroll		

Note: WC = Water Cooled, AC = Air Cooled

Navigant also looked into potentially evaluating the risk for chillers located in part of the occupied space, not in a mechanical room; however, we found the relevant scenarios to be unrealistic due to the refrigerant concentration limit (RCL) detailed in ASHRAE 34. The RCL indicates a safe level of refrigerant from a chiller circuit (or other piece of equipment), that, if released into the enclosed space, would remain at safe concentrations; it is "intended to reduce the risks of acute toxicity, asphyxiation, and flammability hazards in normally occupied, enclosed spaces."[4] The RCL for R-32 is 77 g/m^3 (0.0048 lbm/ft^3), a level that would limit chiller size to unrealistically small sizes for basement applications, below that which is currently manufactured. This study, therefore, does not conduct additional evaluation of basement chiller installations.

The scope of analysis did not include investigation of the comparable predicted risk for outdoor locations other than those listed in Table 2-2, such as ground-mounted installations. For such a scenario, one might expect differences in predicted risk due to:

- Varying levels of accessibility. Many chillers installed at ground level are not protected from unauthorized access by any type of barrier, thereby opening up opportunity for access by untrained personnel. Such increased access may present increased opportunity for the introduction of ignition sources; however the specific location of the chiller will determine to what extent this may be true. Codes and standards may need to be evaluated for potential access-restriction updates.
- Different refrigerant diffusion characteristics, including varying potential for pooling. For example, if a chiller is located on the ground and has a building on one or more sides, this may increase the likelihood of refrigerant pooling and diminish the ability of the wind to rapidly disperse the refrigerant.
- Different installation schedules for new construction. Because a ground-mounted chiller does not require the building structure to be completed prior to installation, the chiller may be installed at a different point in the construction process, thereby changing the amount of time for which the chiller sits idle, fully charged, before it is commissioned.

---

[4] ANSI/ASHRAE Standard 34-2010, Section 3, Definition of Terms.

3. Fault Tree Structure

3.1 Fault Tree Basics

Fault tree analysis (FTA) is an approach to failure/risk analysis which uses boolean logic to combine individual events that may lead to a specific system failure. Figure 3-1 shows example fault tree components. In this figure, diamonds represent initiating event probabilities (e.g., component failures or leaks). Those events can be combined with an AND or an OR gate, as Figure 3-1 shows, to identify a combined probability, represented as a rectangle. The output of an OR gate occurs if any of the inputs occurs. Whereas the output of an AND gate occurs only if all the inputs occur. To calculate predicted risk of the top level event, we use Monte Carlo simulation to randomly simulate failure of individual events. The system failure risk is calculated as the number of top level event failures out of the total number of simulations.

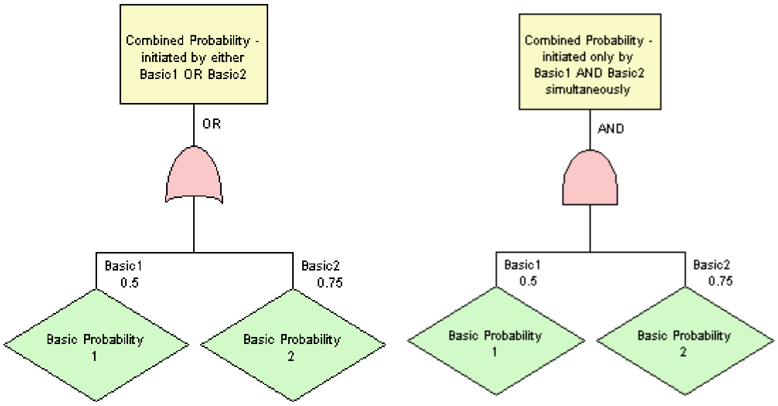


Figure 3-1. Example FTA Branches

3.2 Primary Operating-State Branches

The FTA for each of the scenarios in this analysis contains four primary branches, one for each unique operating state: installation/commissioning (i.e., startup), sitting after installation (prior to initiation of normal operation), servicing, and normal operation. Table 3-1 describes each operating state. For scenario A, where the chiller is located indoors, normal operation is split into two sub-branches, one for when ventilation is running, and the other for when ventilation is off (Table 3-1 discusses both). For all other scenarios in which the chiller is located outdoors, the normal operations state is not divided into two states because only natural ventilation is present. Sections 3.2.1 through 3.2.4 describe each operating state in greater detail.

Table 3-1. Summary of Operating States in Fault Tree Analysis

Operating State	Ventilation Operation	Days per Year
Installation/ commissioning – Installation and commissioning of the chiller itself, both for new construction and replacement.	Ventilation Off	1 (20 days at start of 20 year period)
Sitting, post-installation – After installation, when construction is still underway but the HVAC has not yet been commissioned.	Ventilation Off	1 (20 days at start of 20 year period) [A]
Servicing – Emergency servicing and regularly scheduled periodic maintenance, both annual as well as major overhauls conducted after many years of operation.	Ventilation On – (per code, on when occupied)	5 days/yr.
Normal Operation, ventilation on[B] – Typical operating circumstances when non-emergency ventilation is running (chiller may or may not be running) (e.g., occupied hours of any season).	Ventilation On (~57% of normal operation) [C]	204 days/yr.
Normal Operation, ventilation off[B] – Typical operating circumstances when non-emergency ventilation and chiller are off (e.g., non-occupied hours when the building does not need ventilation).	Ventilation Off (~43% of normal operation) [C]	154 days/yr.

Notes:
A: Highly variable value, which, in extreme cases, could range up to 6 months or more (based on anecdotal evidence from discussions with building managers) if construction is delayed and/or if chiller is put in place as one of the first steps.
B: Ventilation on/off only differentiated for scenario A where the chiller room is ventilated. Remaining scenarios are not impacted by ventilation operation since they are located outdoors.
C: Based on Navigant analysis of the weighted average hours of ventilation operation using CBECS building stock and climate zones. Assumes 20% duty cycle for climate zone 1 (CZ1), 30% for CZ2, 50% for CZ3, 70% for CZ4, and 90% for CZ5.

This analysis does not cover manufacturing and transportation risk, as they are outside of the scope of this study. Figure 3-2 shows the top tree structure for scenario A, where the risk associated with each of the four primary branches is weighted by the expected annual duration for each operating state. The four branches are combined to calculate the total risk. All of the scenarios follow this top structure. The brown triangles link to the individual trees for each operating state.

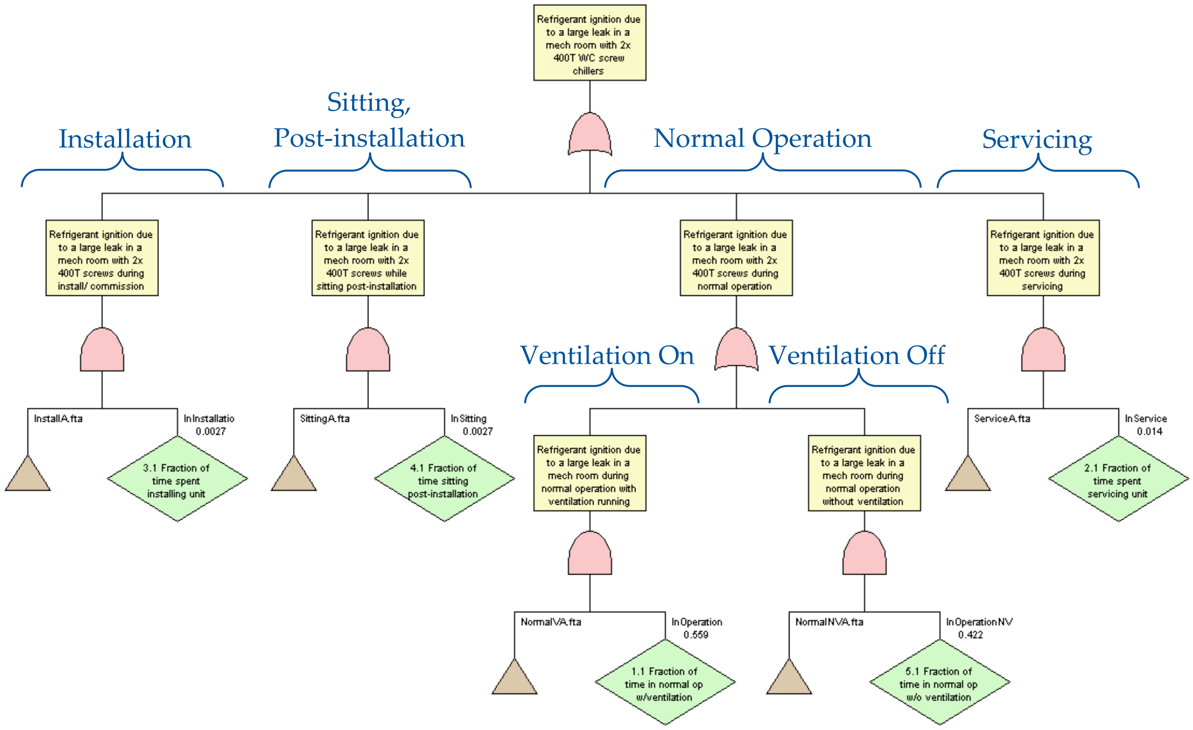


Figure 3-2. Example Top Fault Tree for Scenario A

The annual fractions in this top tree add up to a full year of operation. With this approach, we can analyze the comparable, per-day risk on a given sub-branch (i.e., operating state), as well as the total annual risk for a given scenario.

3.2.1 Installation and Commissioning

The installation and commissioning branch covers the period of time when technicians and/or other contractors put the chiller into place, make all necessary electrical and plumbing connections, charge the machine (if necessary), and commission the system. This state is unique in that neither the chiller nor the ventilation are actually running. With the ventilation off, the likelihood of a leak creating a flammable refrigerant concentration is greater. However, with the chiller off, the likelihood of a leak actually occurring is reduced because the chiller is subject to fewer mechanical forces, such as high and/or fluctuating pressures and vibrations. We believe the primary leak risk is due to accidents in which someone or something comes in contact with the chiller, thereby rupturing a pipe or otherwise causing a rapid release of refrigerant. In such instances, technicians or others are often able to take precautions to reduce the risk of ignition of the leaked refrigerant, however, the impact of such precautions is difficult to quantify.

This branch includes decommissioning and replacement installations (replace on failure) as well as new construction installations. Many replacement installations coincide with major building upgrades and other construction, so the scenario is very similar to a new construction installation. If the replacement installation does not coincide with any major construction, the ignition risks may be reduced relative to a new construction installation. Accident-caused leaks are inherently less likely in this case because there are fewer people, less activity, and less large machinery in the vicinity of the chiller.

3.2.2 Sitting, Post-Installation

The sitting period, after installation, covers the period of time after installation is complete, but the building is still under construction (or under major retrofit). This period is characterized by no ventilation or chiller operation and ongoing construction nearby. As with the installation and commissioning period, the risk of a normal leak is reduced because of the absence of mechanical operating forces, and the risk of an accident-caused leak from the construction work all around is greater.

The duration of this period varies for each installation and depends on the construction schedule and the location of the chiller in the building, among other factors. If the chiller is located in a mechanical room in the basement, it will likely be installed early on in the construction process, and the building will be constructed around it (common for large buildings, particularly high-rise buildings). Conversely, a chiller located on a roof or on the ground next to the building may be installed much later in the construction process and sit for less time before the technicians commission the HVAC.

In extreme circumstances, construction could be interrupted, which would extend the chiller sitting time for many weeks or months. No data are available to provide reasonable estimates for the duration of this period, and anecdotal evidence, based on discussions with technicians and building managers, indicates that the duration of this period is highly variable. We estimate an average duration of 20 days for the purposes of this study.

3.2.3 Servicing

The servicing state includes annual servicing as well as major overhauls and major component replacement. This operating state is characterized by constant ventilation for indoor chillers based on building code requirements for ventilation during occupied hours (based on discussions with technicians and building operators). While certain maintenance activities may require shutdown of the ventilation for a brief period, this will be an infrequent occurrence. Depending on the servicing to be conducted and the time of year of the servicing, the chiller may or may not be running.

An example schedule for a chiller in the northeast of the U.S., based on discussions with local-area building managers, may include up to 2 days of spring preparations, 1 day for a mid to late summer performance check, 1 week for a major overhaul (once every 10 years), and 1 week for major component replacement (once every 10 years). On average, we estimate 5 days of such service during each year.

This operating state does not include periods during which operators, as distinct from technicians, may be in the mechanical room or otherwise near the equipment. Servicing specifically addresses technician-occupied time because such work presents a unique set of ignition risks that would not be present during operator-occupied periods (see Section 4.3 for discussion of ignition sources).

3.2.4 Normal Operation

Normal operation is defined as the typical, day-to-day operation of the chiller, including both on- and off-cycle operation. This state is characterized by few, if any, people in close proximity to the chiller. Normal Operation is the predominant operating state for the chiller; we estimate that it runs in this state for 358 days per year, or 98% of the time.

For outdoor scenarios, B, C, D, and E, normal operation is a single state, however, for scenario A where the chiller is located in a mechanical room, this state is divided into two sub-branches based on whether ventilation is running. The ventilation system, if active, will help evacuate any leaked refrigerant from the room. In general, the ventilation is on during occupied hours and off for unoccupied hours. However, during unoccupied hours, the HVAC system will turn on as necessary to keep the temperature within a pre-determined range. Further, during the hottest part of the cooling season, the chillers and ventilation may run constantly in order to ensure that the building is at the set temperature when it is scheduled to be occupied in the morning.

- **Normal Operations, Ventilation On –** includes all hours scheduled for occupancy, per building code, as well as any periods scheduled for no occupancy when space conditioning is required and the HVAC system is running. For a typical office building, the ventilation system may turn on at 7 am on weekdays, and shut down at 6 pm. On weekends, the ventilation may be on for some period of time depending on when it is scheduled to be occupied.
- **Normal Operations, Ventilation Off –** includes all hours scheduled for no occupancy, per building code, EXCEPT for those when the HVAC is actively running to condition the space. For constantly-occupied buildings, such as hospitals, this operating state does not exist (the duration for each operating state is a weighted average of common building types).

The ventilation that defines the Normal Operation sub-states, above, is only the standard ventilation that may be on or off depending on when the building is schedule to be occupied or unoccupied. Emergency ventilation, as defined by ASHRAE-15 sections 8.11.3-8.11.5, is addressed separately in our analysis and is based on the risk of failure of the refrigerant monitor. As discussed in Section 4.4.2 (Table 4-4), our analysis shows that when the emergency ventilation is operational, the predicted risk of flammable refrigerant concentration buildup is negligible.

From discussion with building managers, we found anecdotal evidence to suggest that some mechanical rooms are not built to code and have no ventilation except for emergency exhaust ventilation that activates when the air must be evacuated rapidly. However, since this study assumes that mechanical rooms are built to code, we do not cover such exceptions.

4. Input Modeling

4.1 Summary

Each of the four primary branches (one each for normal operation, servicing, and installation/commissioning, see section 3.2, above) contains three primary variables (probabilities) that drive the ignition risk:

- Large refrigerant leak (capable of reaching flammable concentrations)
- Presence of active ignition source during period of flammable refrigerant buildup
- Colocation potential of flammable refrigerant and active ignition source

The sections below, discuss the data collection, modeling, and analysis used to develop FTA inputs for each of these variables.

4.2 Large Refrigerant-Leak Data

4.2.1 Process

To help characterize the frequency of leaks in chillers accurately, the PMS members offered to provide leak data to Navigant from their respective organizations. We coordinated with PMS members to collect the leak frequency information for relevant chiller product lines, along with corresponding shipment volume data for each product.

Navigant parsed and structured this data into a format that could be consistently compared across similar products from different manufacturers. The team removed extraneous, irrelevant, and incomplete data, and then sorted the data according to the five chiller configurations examined in this project.

After editing the data, Navigant used the sales volume data to calculate weighted industry-wide averages of chiller leak frequencies for each of the chiller types under investigation. Figure 4-1 summarizes the steps that Navigant followed in developing estimates of chiller leak frequencies.

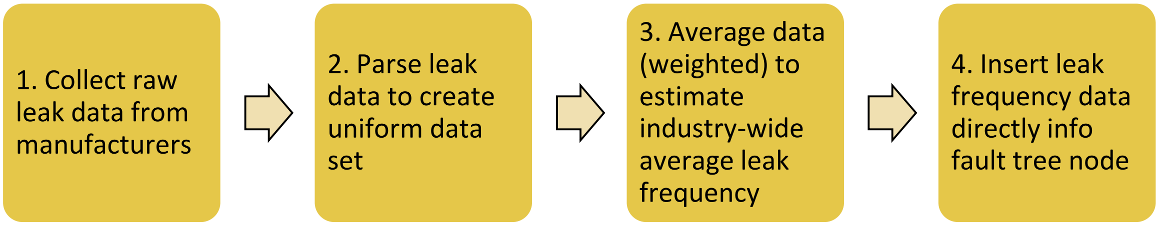


Figure 4-1. Leak Data Analysis and Collection Process

4.2.2 Data Collection

Manufacturers collect data on refrigerant leaks and other repairs through their warranty departments for chillers produced and installed in the past several years. The PMS gathered warranty records relevant to leak claims and provided those records, along with sales volume data for those years, to the analysis team. Collectively, the PMS members that provided data represent a majority of the U.S. chiller market.

The PMS-member chiller manufacturers provided data to Navigant in two different forms. One manufacturer provided aggregated leak frequencies, which contained average leak frequencies across entire product families as a function of time. The team used the data from this manufacturer as provided, since no further granularity could be discerned on a per-incident basis. A drawback of aggregated data is that the records cannot be checked on an individual basis, or broken down to a higher level of detail than that provided by the data supplier.

All of the other manufacturers provided leak data in the form of warranty records. Those data consisted of individual records for claims made to the OEM warranty department, documenting all replacement parts and labor needed for each service call. The team parsed the data to remove claims that were unrelated to this analysis (e.g., outside of analysis time frame, out-of-scope chiller type, or not leak-related), and to highlight individual significant leak incidents. A drawback of warranty data is the high level of detail, which required the team to use its best judgment regarding the relevance of certain data.

4.2.3 Data Analysis

Navigant parsed the records into categories that paralleled the scenarios described in Section 2.2, above. However, since the data spanned entire product lines and encompassed chiller configurations other than the five under consideration, the team had to align the real-world data with the analytical plan.

The warranty record data that PMS members provided was extremely detailed, including every line item expense involved in each warranty repair. The team first removed duplicate entries corresponding to the same date and event, thereby eliminating up to dozens of line items under a single warranty call. The team then distilled the data so that there remained only a single line item (including model number, compressor type, cooling capacity, and condenser cooling type) corresponding to each individual leak warranty claim. Additionally, the team removed warranty claims that were unrelated to chiller leaks.

Per guidance from the PMS, the team focused only on leak frequencies of newer units; due to substantial differences in technology, the leak frequencies of older units would not be representative of leak frequencies in newer models using the proposed refrigerants. The industry generally provides a standard warranty on chillers that extends 18 months from shipment or 12 months from startup, whichever is sooner. Navigant eliminated the data for leaks that occurred outside of that timeframe.[5]

With a cleaned and refined dataset, Navigant then summed the leaks by manufacturer into two different categories: startup leaks and rest-of-warranty leaks. We defined “startup leaks” as those occurring within the first two to three weeks of recorded operation (depending on resolution of available data), based upon the installation date provided in the chiller records. The team defined “rest-of-warranty

---

[5] The warranty records contained some events on chillers older than 18 months. Discussion with the PMS member organizations verified that these were special warranty exceptions made on a per-case basis. Since they were unique events, and were not representative of the performance of the entire population of chillers of this age, Navigant removed those records from the analysis.

leaks" as those occurring from the end of the startup period until the end of the warranty period. We did not categorize rest-of-warranty leaks into any additional time periods.

The team segmented the warranty leak records by chiller size and type, corresponding to the five chiller types to be analyzed. When the size range of a chiller family spanned one of the sizes being analyzed (100, 200, or 400 Ton), we considered the data for that entire family to be representative of the size of interest. For example, for a family of air-cooled screw chillers that is available in sizes from 150-300 tons, the team used the data for the entire family for the 200-ton air-cooled screw scenario.

Finally, the team used the product shipment data from each manufacturer, along with the number of reported leaks for each product type, to calculate industry-wide weighted-average leak frequencies. We calculated startup and rest-of-warranty leak frequencies for each of the five chiller configurations analyzed and, where necessary, normalized extended warranty data to fit the 12 month analysis period. Table 4-1 shows the aggregate results of the leak frequency analysis (on a percentage basis), representing the total number of leaks in the population divided by the size of the population. In the ensuing analyses, the team assumed that these leak frequencies could be applied as representative of the leak potential of any single chiller installed and operated over a one-year period.

Table 4-1. Leak Frequency Data Summary

Scenario	Chiller Type	Leak Frequencies		
		Startup	Rest of Warranty Period	Annual Total*
A	400T WC Screw	1.6%	5.4%	7.0%
B, D	200T AC Screw	2.3%	6.6%	8.9%
C, E	100T AC Scroll	1.2%	3.4%	4.6%

*Leak frequencies in the table do not all sum accurately due to rounding

We found that startup leaks occur in roughly 1-2% of all units, and overall leak frequencies range from 3% to more than 6% in the first year of operation. The data also show that leak frequencies generally increase with the capacity of the chiller. Such an inference is likely beyond the statistical precision of the data for startup leaks, but is evident in the rest-of-warranty and annual leak frequencies. Additional data provided by the PMS, but not utilized in this analysis, contained leak frequencies for very large centrifugal chillers; these data showed trends of higher leak frequencies in large units, in agreement with the overall trend seen in Table 4-1.

The leak frequencies in the chiller population represent all leaks that technicians addressed and recorded via warranty claims. While it is possible that this misses a few leaks (e.g., if a warranty claim was never filed, or the leak was slow enough that nobody noticed), we assume that the calculated leak frequency applies to all leaks of any size. Based on discussions with technicians, we estimate that 5% of all leaks are sufficiently large to cause a flammable concentration above the LFL to build up within the space. In other words, most leaks are small leaks and even though they can release large amounts of refrigerant over time, such leaks are readily diluted and dispersed, and cannot cause flammable concentrations.

No manufacturer data are available to distinguish large leaks from small leaks. As well, there is no clear measurement that would allow manufacturers to grade the ability of a leak to cause a flammable concentration in the first place. Due to their close involvement with chiller issues, service technicians are the best source of information on the frequency of leaks that are large enough to cause build-up of flammable concentrations. This report recognizes that the estimate given by service technicians is anecdotal and not precise. Therefore, a sensitivity analysis given in Section 5.2 addresses the matter.

Industry consensus is that small pinhole leaks do not produce a flammable concentration.[6] Therefore, we did not account for the volume of refrigerant lost during a given leak, since any large leak – those that could produce a flammable concentration – will presumably lose all, or nearly all, of its charge. We also assume that any leak small enough for a technician to stop without losing almost all of the charge is too small to create a flammable concentration; e.g., a pinhole leak which only loses a significant portion of the charge over a period of days or weeks.

We use these assumptions for two reasons:

1. By the time a technician arrives to stop the loss of refrigerant, a large leak will most likely have allowed all, or nearly all, of the refrigerant to escape. In the data analyzed there may be a few cases where a large leak could have been stopped by a nearby technician who was aware of the leak and could isolate the leaking component, but that is an unusual scenario.
2. The assumption represents a conservative estimate.

This analysis applies only to the leak frequency, not the rate at which the chiller may lose refrigerant. The leak frequency data feeds directly into the FTA as discussed in Section 4.1, above. No data were available to specifically define leak rates, so we produce FTA inputs using two models as described in Section 4.3.

Variations in the scope, format, and other characteristics of the data introduced uncertainty in the analysis beyond those issues already discussed (i.e., data from outside the warranty period and irrelevant, non-leak records). Two such factors of concern were:

1. Incompleteness in the reporting of the warranty claim records. This could include incidents which, for any number of reasons, may have not been reported as warranty claims.
2. The wide range of sizes included in some chiller families resulted in some data being applied to multiple scenarios.

The team assumed that these factors did not significantly affect the comprehensiveness and representativeness of the data.

4.3 *Potential Ignition Sources*

The team used data from the literature review, discussions with PMS members, technician interviews, and other sources to compile a list of ignition sources potentially present near chillers. For each potential ignition source, Navigant researched the frequency and duration of the source being present. The

---

[6] Kataoka O, Ishida S, and Hirakawa T, "Experimental and numerical analyses of refrigerant leaks in a closed room," *ASHRAE Transactions* 105, Part 2, Paper SE-99-19-2 (1999); risk studies consistently focus only on burst-type scenarios – the implicit conclusion is that pinhole leaks enable rapid diffusion and no ignition risk.

estimated ignition source frequencies and durations were critical inputs for the coincidence model (see Section 4.4.3).

The identified ignition sources are as follows:

- **Hot surface –** The team's model represented the exhaust, or other portions of an operating diesel generator, as a hot surface. Those components can reach 700°-1300° Fahrenheit during operation.[7] While R-32 has an auto-ignition temperature (AIT) 1198°F, which is at the high end of this range, R-1234yf has an AIT of only 761°F and R-1234ze(E) has an AIT of only 694°F. Generator-manufacturer literature states that generators should be run a minimum of once a month for 30 minutes, a frequency greater than typical emergency use of about once per year. The team assumed that generators would be present in the mechanical room scenario; therefore, the team estimated the hot surface to be present in the mechanical room once a month for 30 minutes.
- **Electrical spark –** Mechanical rooms are subject to requirements of mechanical codes that mandate non-sparking fans and other safe components. However, high-voltage contactors do present a potential source of electrical sparks in a mechanical room. These generally function without sparking for many hundreds of thousands of cycles, so the team used a conservative estimate that four times a year a contactor somewhere in the mechanical room will fail, and therefore spark during each actuation, over a period of 72 hours. Electric motors could also, in theory, present a sparking hazard. Ammonia systems currently have an exemption from ASHRAE 15 requirements for explosion-proof motors and motor control centers. Industry experts suggest the same exemption be applied for all Class 2L systems. Accordingly, we investigated spark potential from each relevant motor type. DC motors with brushes will spark; however, they are unlikely to be present in the typical mechanical room. Brushless DC motors, which do not spark under normal operation, anecdotally appear to be increasingly common; however their current penetration is assumed to be insignificant at this time. While a mechanical room could contain a single phase AC motor, the current manufacturing trend is to move away from sparking mechanical switches toward solid-state switches that do not spark. Three-phase motors, the most common type in a mechanical room, can spark, but only due to certain failure modes, such as overheating and insulation failure. Such failures and associated spark occurrences are statistically insignificant over the life of the motor compared to the risk of contactor failure and is therefore not evaluated further in this analysis.[8]
- **Boiler –** Boilers installed per the requirements of ASHRAE 15 include full ducting to prevent room air from being used in combustion, or employ a refrigerant sensor to stop combustion in the presence of a leak.[9] Therefore, boilers installed to code should not present a significant risk.

---

[7] The published auto-ignition temperature (AIT) per ASTM test methods of R-32 is 1198°F, and that of R-1234yf is 761°F. Some industry researchers have suggested that these AIT values may be too low to use as allowable hot surface temperature limits for nearby equipment, and that real-world auto-ignition events from hot surfaces may occur at significantly higher temperatures. However, for the purpose of this study we assumed the published AIT of 761°F for R-1234yf to be representative of a highest-risk scenario, and thus assumed that generator components are sufficiently hot to ignite that refrigerant. Discussions with the PMS indicate that future changes to IEC 60335-2-40 codes may allow temperatures up to 1290°F based on industry research.

[8] Personal correspondence with motor industry subject matter experts

[9] ASHRAE 15 is a safety standard referenced by building codes that establishes mechanical room design requirements, and in the case of using flammable refrigerants, it includes restrictions on flame-producing devices

However, we estimate that approximately 1% of boilers will have some level of faulty installation and could pose a potential ignition source. We modeled both standing pilot and electronic ignition boilers as a constant ignition threat during operation, with a 50% annual duty cycle. Data show that even for electronic ignition boilers the duty cycle is high enough, compared to the order of magnitude of leak duration that the boiler would light at some point during a leak. The team used this assumption only for mechanical rooms; we considered this ignition source to be inapplicable to outdoor installations.

- **Non-chiller technicians using tools** – Based on estimates of repair frequencies and durations, we estimate that a technician could be in the presence of a chiller, using sparking tools that pose an ignition risk, for a two-hour period once per month. This risk is applicable to all scenarios.
- **Cigarette lighters** – Literature shows that while a lit cigarette cannot ignite the A2L refrigerants considered here, a cigarette lighter may be capable of doing so. In a mechanical room setting, the team assumed that only technicians would have access, and that such individuals would likely be trained in proper safety protocols; thus, the risk would be low. We estimated that a lighter might be lit only once per year in a mechanical room. We applied the same assumption to the rooftop, given the similar access restrictions in that setting. Some outdoor installations, such as those at ground level (not covered in this analysis) may not have restricted access, which would change the necessary assumptions for ignition sources (see Section 2.2 for discussion of additional distinctions).

Table 4-2 shows the ignition sources that the team considered for each scenario analyzed.

Table 4-2. Ignition Sources Considered, by Scenario

Ignition Source	**Mechanical Room (A)**	Rooftop - Unrestricted Airflow (B, C)*	Rooftop - Restricted Airflow (D, E)
Hot surface	Yes	No	No
Electrical spark	Yes	No	No
Boiler - not to code	Yes	No	No
Technician using tools	Yes	No	Yes
Cigarette lighter	Yes	No	Yes

* Ignition sources do not apply to unrestricted-airflow rooftop scenarios because no flammable concentration of refrigerant is maintained (See Table 4-4, below).

---

such as boilers and hot water heaters. Per section 8.12, when refrigerants of Group A2, A3, B2, or B3 (all of which are more flammable than A2L refrigerants which we include in this analysis) are used, no flame-producing devices may be permanently installed.

4.4 *Refrigerant Leak and Ignition Source Modeling*

4.4.1 Methodology

In evaluating the probability of refrigerant ignition, the team developed two separate analytical models to help characterize the complex issue of leak rate and dispersion characteristics:

1. Dispersion model: This model predicts whether a given leak would result in a refrigerant concentration exceeding the LFL and, if so, how long that concentration would persist above the LFL and below the UFL. The dispersion model accepts two sets of inputs: *chiller characteristic data* and *physical characteristics of the chiller location*. Section 4.4.2 describes this model.
2. Coincidence model: The coincidence model predicts the probability that a given leak that produces a flammable refrigerant concentration would coincide with the presence of an ignition source. This model uses data on potential ignition sources, coupled with the results from the dispersion model. Section 4.4.3 describes this model.

Figure 4-2 shows a flow diagram of the ignition probability modeling process, including the dispersion and coincidence models and their respective inputs and outputs.

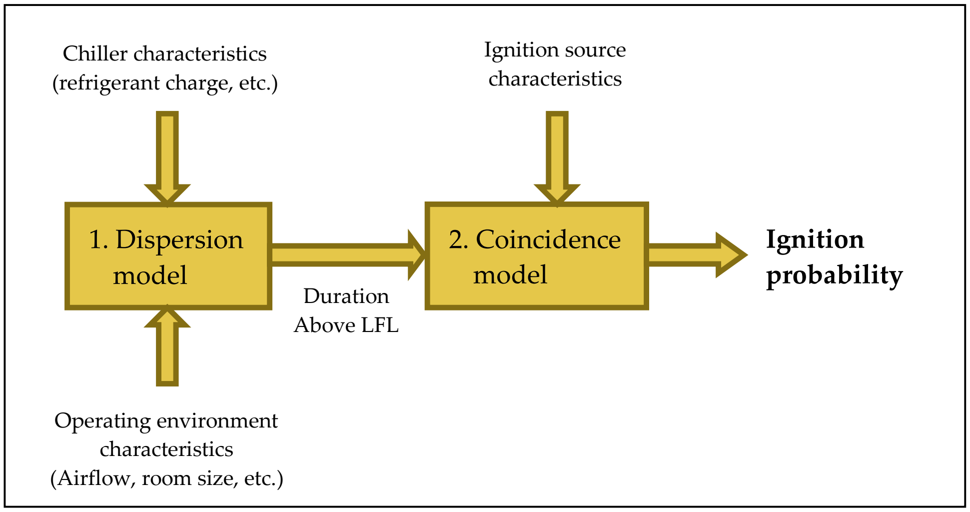


Figure 4-2. Ignition Probability Modeling Flow Diagram

4.4.2 Leak Dispersion Analysis

As mentioned, the dispersion model calculates the dispersion effects of refrigerant leaks in each scenario, and quantifies the potential for a flammable refrigerant concentration to form. In developing the model, Navigant based its assumptions on the results of past studies and the literature review. Navigant's general approach is conservative to ensure that final risk calculations never underestimate the ignition risks. Such an approach is particularly important for assumptions that relate to leak rates and dispersion characteristics, where results vary significantly for each individual installation and extensive modeling and testing would be required to understand the nature of each leak. The underlying assumptions of the model included the following:

- Two strata of refrigerant exist in the space, with the lower stratum having twice the refrigerant concentration of the upper (per estimates based upon past CFD leak analyses).
- Complete mixing of the refrigerant and air within each strata; this is assumed to be due, in part, to the presence of ventilation in the space (per the results of Kataoka et al.[10] and past CFD modeling for leak analysis studies). Actual mixing is highly dependent on airflow. This assumption provides a conservative-case approximation for the vertical dispersion of the refrigerant.
- No horizontal gradient exists in the space, due to rapid dispersion. As with vertical dispersion behavior (above), actual mixing is highly dependent on airflow. For consistency in modeling, this assumption provides a conservative-case approximation for the horizontal dispersion of the refrigerant.
- The ventilation system exhausts the diffused refrigerant and air mixture at a constant rate. Therefore, as the refrigerant concentration increases, the rate at which the ventilation system removes refrigerant increases proportionally.

The numerical inputs for each of the scenarios are as follows:

- **Average refrigerant charge (mass)** was estimated for each of the three chiller types by examining OEM literature.
- **Leak rate** was based on chiller charges, plus the assumption of very significant refrigerant leaks. The leak rates used ranged from 25 lbm per hour to 550 lbm per hour (rapid loss of all charge).
- **Mechanical room ventilation** was based on ASHRAE Standard 15-2010, which requires that mechanical rooms contain two levels of ventilation: one for standard occupied use and another for emergency exhaust if a refrigerant monitor senses a leak. The team modeled both of these scenarios in the dispersion analysis. The first level of ventilation simulated a scenario in which a refrigerant monitor was malfunctioning during a leak; hence the exhaust ventilation did not turn on.
- **Obstructed rooftop airflow estimates** were based on the free-air aperture requirements of ASHRAE 15 (section 8.11.5) and the assumption of consistent air movement in the atmosphere at approximately 0.5 mph.
- **Properties of refrigerants and air** were obtained from industry papers and NIST REFPROP 9.0 software.
- **Room/space sizes** were developed based on building codes, such as the International Mechanical Code and California Mechanical Code, plus other literature. As an example, a diagram of the layout of a typical large mechanical room is shown in Figure 4-3.

---

[10] Kataoka O, Ishida S, and Hirakawa T, “Experimental and numerical analyses of refrigerant leaks in a closed room,” *ASHRAE Transactions* 105, Part 2, Paper SE-99-19-2 (1999).

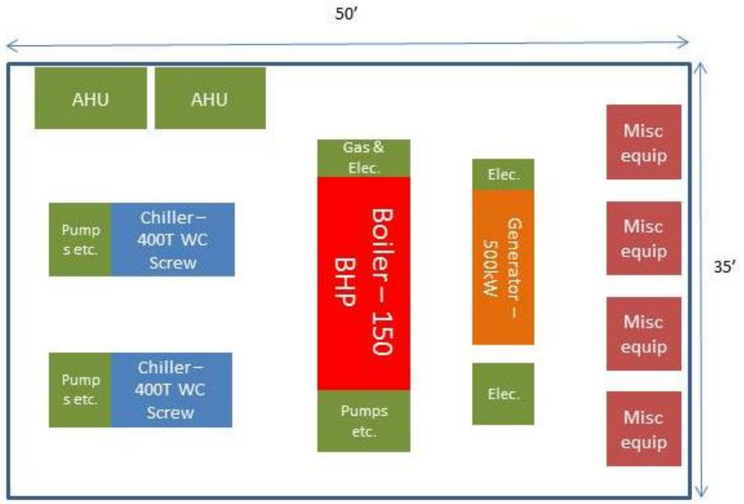


Figure 4-3. Example Mechanical Room Layout

Using the above inputs to quantify the chiller's surroundings, the model used simple mass and volume accounting and incremental time steps to model the refrigerant concentration in a constrained location during and after a refrigerant leak. We simulated refrigerant being released into the ambient air at a constant rate (lbm per hour) per time step until the chiller's charge was fully released. While the leak rate would decrease over time in a real chiller leak due to the gradual decrease in pressure differential, this analysis assumes a constant leak rate to approximate a conservative estimate to what would otherwise be a substantially more complex analysis.

Table 4-3 shows the assumptions regarding charge size for each scenario.

Table 4-3. Refrigerant Charge Assumptions (R-32 as Example Refrigerant)

Scenario	Chiller Type	Location	Assumed lbm/RT of Refrigerant*	Charge Size (lbm)
A	400T WC Screw	Mech Room	2.5	1,000
B	200T AC Screw	Rooftop	2.05	410
C	100T AC Scroll	Rooftop	1.1	110
D	200T AC Screw	Rooftop	2.05	410
E	100T AC Scroll	Rooftop	1.1	110

* Based on review of manufacturer literature for major equipment lines by desired type and tonnage offered by high-market-share manufacturers

The model assumed full and instantaneous mixing (of air and refrigerant) within each of the previously described strata. In each time step, the exhaust system removed a volume of the air/refrigerant mixture at the specified ventilation rate, and replaced this air with an equal volume of fresh air, minus the volume of any newly leaked refrigerant entering the room. This was followed by a calculation of refrigerant concentrations in the room in each of the two vertical strata. The model then checked to see whether the concentration at each fixed time interval was between the LFL and UFL in either stratum, and finally summed the number of intervals that were both above the LFL and below the UFL to yield a total time flammable duration for a given leak.

For normal operations in scenario A with no mechanical ventilation running, we modeled the representative airflow based on the envelope component infiltration properties in ASHRAE 90.1 for a typical mechanical room.[11] Unlike other studied variables, in this operating state, the lower the infiltration air flow, the greater the risk of a buildup of a flammable refrigerant concentration. As such, a tighter envelope will cause an increase in the predicted risk for this scenario. To estimate a representative air exchange rate, we assumed that two of the walls would be exterior-facing and thus subject to baseline infiltration at a rate of 0.12 CFM per square foot for the two walls (660 square feet). We assume two 8′ by 6′ sets of opaque double doors, one on each wall, with a baseline infiltration rate of 0.4 CFM/square foot. The total infiltration is 106 CFM.

The output of the dispersion model was an estimate of whether, and for what duration, a fully mixed flammable concentration could develop in the given scenario (Table 4-4 and Table 4-5).

Table 4-4. Dispersion Model Findings of Flammable Concentrations, By Scenario

Relevant Scenarios	Dispersion Model	Concentration above LFL found?	Concentration above UFL found?
A	400T WC Screw (*Large mechanical room*) with non-functioning exhaust ventilation*	No	No
	400T WC Screw (*Small mechanical room*) with non-functioning exhaust ventilation*	Yes	No
	400T WC Screw (*All mechanical rooms) with functioning exhaust ventilation***	No	No
	400T WC Screw (*All mechanical rooms) with no ventilation*	Yes	No
B, C	100T AC Scroll, 200T AC Screw *Unrestricted-airflow rooftop*	No	No
D, E	100T AC Scroll, 200T AC Screw *Restricted-airflow rooftop (or pit)*	Yes	No

* The small mechanical room is defined as 750 square feet (30′ x 25′) with 12′ ceilings. The large mechanical room is defined as 1400 square feet (40′ x 35′) or larger with 12′ ceilings.
** Exhaust Ventilation defined using ASHRAE 15specifications

In three scenarios the model showed that dispersed flammable concentrations were not likely to occur:

- Rooftops with unrestricted airflow
- Mechanical rooms with fully functioning ventilation per ASHRAE 15
- Large mechanical rooms of 1400 square feet (e.g., 40′x35′ with 12′ ceilings) or larger

---

[11] Available as Table 1 (page 6) in Gowri et. al. “Infiltration Modeling Guidelines for Commercial Building Energy Analysis,” Pacific Northwest National Laboratory, 2009. Available from: http://www.energy.ca.gov/title24/2013standards/rulemaking/documents/public_comments/45-day/2012-05-15_Infiltration_Modeling_Guidelines_for_Commercial_Building_Energy_Analysis_TN-65229.pdf

In those instances, the airflow is predicted to always be sufficient to prevent accumulation to the LFL. For large mechanical rooms with non-operational exhaust ventilation, the dispersion model predicts that even very rapid leaks would not produce a dispersed refrigerant concentration above the LFL. This is consistent with results seen in other analyses, including CFD modeling performed for a residential AC project.

The team ran the analysis for a smaller mechanical room of 750 square feet (30′ x 25′ with 12′ ceilings) to find a max-risk fully-dispersed condition (i.e. the condition with the longest flammable concentration persistence), and additionally accounted for the threat of a refrigerant leak in a large mechanical room by modeling the separate scenario of a refrigerant jet impinging upon an ignition source.

In instances where a dispersed flammable concentration could be sustained, the team ran the dispersion analysis calculations using leak rates ranging from 25 to 550 pounds per hour to find the maximum-risk scenario. The team considered "maximum risk" to be the scenario which produces the longest period of time with a flammable concentration, thus maximizing the likelihood of that concentration coexisting with an ignition source. This does not necessarily coincide with the most common leaks, or even the fastest leaks.

In order to find this maximum risk situation, the team plotted the time for which the concentration remained within flammability limits as a function of leak rate for each scenario. The team selected the leak rate which produced the longest duration with a flammable concentration as its worst-case scenario for analysis. A sample plot of duration with flammable concentration versus leak rate for one scenario is shown in Figure 4-4. Appendix A contains a full set of plots for each scenario. Note that because no scenarios exhibit concentrations above the UFL, each plot measures the "Duration above LFL (hours)," in which flammable concentrations exist for the entire period.

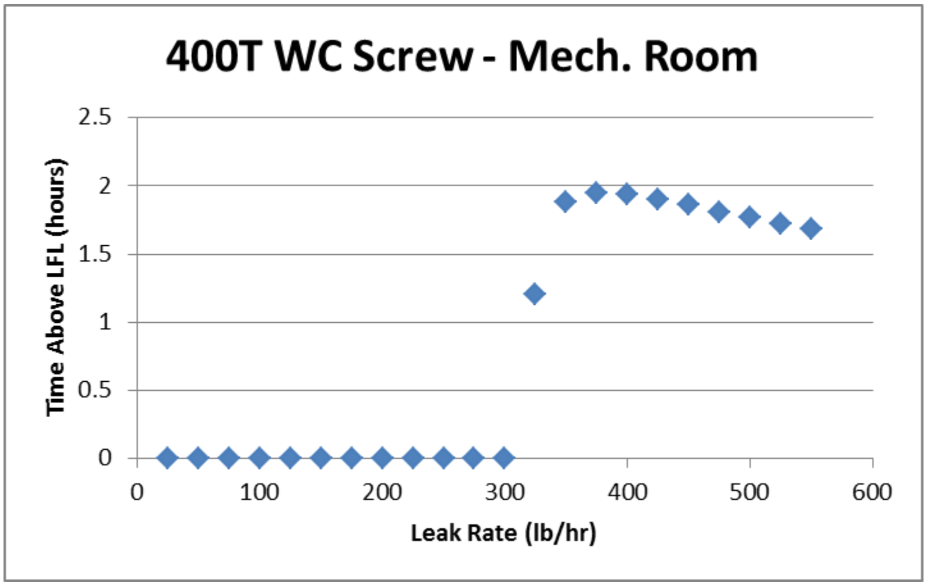


Figure 4-4. Example Plot of Duration above LFL versus Leak Rate (Scenario A, with no functioning exhaust ventilation)

Table 4-5 shows the overall quantitative results of the leak dispersion analysis calculations.

Table 4-5. Refrigerant Leakage Calculation Results (R-32 as Example Refrigerant)

Scenario	Chiller Type	Location	Max-Risk Leak Rate (lbm/hr)	Time to Leak Full Charge (hr)	Duration Concentration is Flammable (hr)
A	400T WC Screw	Mech Room – with Ventilation	375	2.7	2.0 **
		Mech Room – No Ventilation	100	10	6.7
B	200T AC Screw	Rooftop	450	0.9	0 ***
C	100T AC Scroll	Rooftop	550	0.2	0 ***
D	200T AC Screw	Rooftop	450	0.9	0.7
E	100T AC Scroll	Rooftop	550	0.2	0.2

* For two-circuit chillers, the charge size listed here represents the charge in a single circuit.

** Represents only the small mechanical room as shown in Table 4-4, above, as this is the only mechanical room scenario in which a flammable concentration will accumulate.

*** No flammable concentration maintained for unrestricted-airflow rooftop scenarios (B, C) See Table 4-4, above.

4.4.3 Ignition and Refrigerant Coincidence Modeling

The team then developed the coincidence model to predict the probability that leaked refrigerant could come into contact with a potential ignition source. To quantify this risk we gathered additional inputs regarding ignition sources (see section 4.3, above), and coupled that data with the dispersion analysis results in the coincidence model.

The two main inputs into the coincidence model consisted of: (1) the maximum calculated leak duration from the dispersion analysis, and (2) the ignition source frequency and duration data. The model calculates the probability of a leak coinciding with a potential ignition source having greater than the minimum ignition energy (MIE).

The model determines the joint probability over a one year period of the two factors necessary for ignition (concentration above the LFL and the presence of an ignition source). For each ignition source, the team populated the yearlong period with potential ignition events, per the frequencies and durations discussed in Section 4.4.1. The model assumes a uniform distribution of ignition events throughout the year; any overlap of ignition events is assumed to be a plausible coincidence. The model then counted the fixed time intervals in which a leak event overlapped with the presence of an ignition source, and divided it by the number of time intervals to yield the final probability. The team calculated this probability for each applicable combination of chiller type and ignition source.

For the 400T water-cooled screw chiller in a mechanical room, the dispersion model showed that refrigerant concentration would only be above the LFL in small mechanical rooms, as discussed in Section 4.4.2. However, to ensure that the model covered extraordinary refrigerant leak risk conditions in a large mechanical room, the coincidence model extended the original scenario with two situations, using the same leak frequencies and durations: (1) a dispersed leak that would allow the concentration in the room to build up beyond the LFL, such as would be the case in a small mechanical room, and (2) a concentrated refrigerant jet caused by a leak that extended into the room. For the jet scenario, the team used a 25% probability of the jet impinging upon any ignition source that may be present at the time the leak was occurring.

The team estimated that the jet scenario would occur for 75% of all leaks and that the dispersion scenario would occur 25% of the time. Therefore, the probabilities used for the 400T mechanical room scenario were weighted averages of the results of the jet and dispersion scenarios. This applies to normal operations and servicing (with functioning exhaust ventilation) for the mechanical room scenario only. The team did not analyze the jet leak situation for other scenarios because in each case the uniform dispersion situation presented the greater risk.

For each chiller type, the final output of the coincidence model was a set of probabilities of a leak coinciding with each of the potential ignition sources. This served as input into the fault tree. Table 4-6 shows these probabilities for the scenarios and ignition sources considered.

Table 4-6. Leak and Ignition Source Coincidence Probabilities

Ignition Source	Scenario:			
	A		D	E
	400T WC Screw - Mech. Room with Ventilation	400T WC Screw - Mech. Room No ventilation	200T AC Screw – Roof	100T AC Scroll – Roof
Electrical spark	0.015	0.016	N.A.	N.A.
Hot surface	0.0016	0.005	N.A.	N.A.
Boiler - not to code	0.24	0.29	N.A.	N.A.
Technician using tools	0.0027	0.006	0.004	0.003
Cigarette lighter	0.0002	0.0004	0.0001	0.0001

* Note that rooftop scenarios with unrestricted airflow (B and C) are excluded from this table. Flammable concentrations were not predicted to build up in those scenarios due to rapid dispersion of the refrigerant.

4.4.4 Colocation of Refrigerant and Ignition Source

Colocation, that is, the presence of refrigerant vapor and an ignition source in the same location at the same time, is required for there to be any risk of ignition. If, for example, leaked refrigerant vapor is contained to part of a room (e.g., a depressed pit), but the only nearby ignition sources are located in another part of the room, then there exists no risk of ignition. Depending on the particular scenario, colocation may be due to any of the following factors:

- Ventilation failure – for indoor scenarios, if the ventilation system malfunctions (or the exhaust-stage ventilation fails to actuate), the refrigerant will no longer be removed from the space, and will build up into greater concentrations.
- Refrigerant leak monitor malfunction – For mechanical rooms, in which an exhaust-stage ventilation system is required, the inability to detect the refrigerant leak will prevent the exhaust ventilation from operating.
- Leak self-diagnosis – This refers to the potential for the chiller (or building management system) to identify that a leak may have occurred and either take automatic precautions (e.g., shut down the machine), or notify an operator so that he or she may take manual precautions (e.g., evacuate

nearby personnel and shut down any potential ignition sources). Current capabilities may be limited to low-pressure alarms or low-pressure switches; such capabilities, though they may allow a large loss of refrigerant before initiating the alarm, still can allow for valuable manual or automatic precautions. This variable is not based on the ability to sense a leak of a specific percentage of the total charge, but rather to capture any existing backup capability to the refrigerant leak monitor. Newer chiller system may include additional self-diagnosis capabilities, which could be accounted for in this variable.

The inputs for these variables come from research on the failure probability of the relevant system component(s).

5. Fault Tree Analysis Results

5.1 Overall Risk Results

To calculate the risk of ignition we ran Monte Carlo simulations, with 10 million iterations, on each fault tree. The lowest-risk scenario is scenario C (100 Ton AC scroll chiller on a rooftop with unrestricted airflow), at 1.0 E-6, or 1 ignition per million units per year. Table 5-1 shows the individual calculated risks for each scenario.

Table 5-1. Fault Tree Analysis Results by Scenario (in Order of Risk)

	Scenario	Chiller	Location	Annual Risk of Ignition*
Increasing Risk→	**A**	Single-Circuit 400T WC Screw (2x)	Mechanical Room	4.2 E-6
	E	200T AC Screw	Rooftop (restricted airflow)	2.0 E-6
	B	200T AC Screw	Rooftop (unrestricted airflow)	1.4 E-6
	E	100T AC Scroll	Rooftop (restricted airflow)	1.2 E-6
	C	100T AC Scroll	Rooftop (unrestricted airflow)	8.3 E-7

* Units for Risk are occurrences (refrigerant ignitions) per scenario per year

To quantify the risk of ignition during the different operating states of each scenario, we calculated the predicted risk for the individual branches of the fault tree. For scenarios B-E we did analyze normal operations differently with regards to ventilation operation because for each of these scenarios the chiller is located outdoors. Table 5-2 shows the risk components for each operating state, on a daily basis.

Table 5-2. Daily FTA Results by Operating State

	Daily Risk of Ignition (Occurrences/Installation/Day) by Operating State (10^-7)			
Scenario	Normal Operation*	Servicing	Installation / Commissioning	Sitting Post-Installation
A	0.11 (w/Ventilation) 0.0019 (w/o Ventilation)	2.4	6.3	0.051
B	0.00025	1.6	4.7	0.00055
C	0.000014	1.1	2.4	0.00027
D	0.010	1.7	4.8	0.0093
E	0.0038	1.2	2.5	0.0066

Figure 5-1 shows the comprehensive results of the FTA on a daily basis, including both the total frequencies of refrigerant ignition, as well as the individual frequencies for normal operation, servicing, installation/commissioning, and sitting post-installation. The total predicted risk is much lower than the individual predicted risk for either servicing or installation because the total risk is a weighted sum of the individual predictions, and the weighting factors for servicing and installation are very small. However, note that for scenarios B and C, the Normal Operations risk is smaller than the risk for servicing or installation by more than 3 and 5 orders of magnitude, respectively. As a result, the servicing and installation risk plays a much greater role in the total risk as compared to the other scenarios.

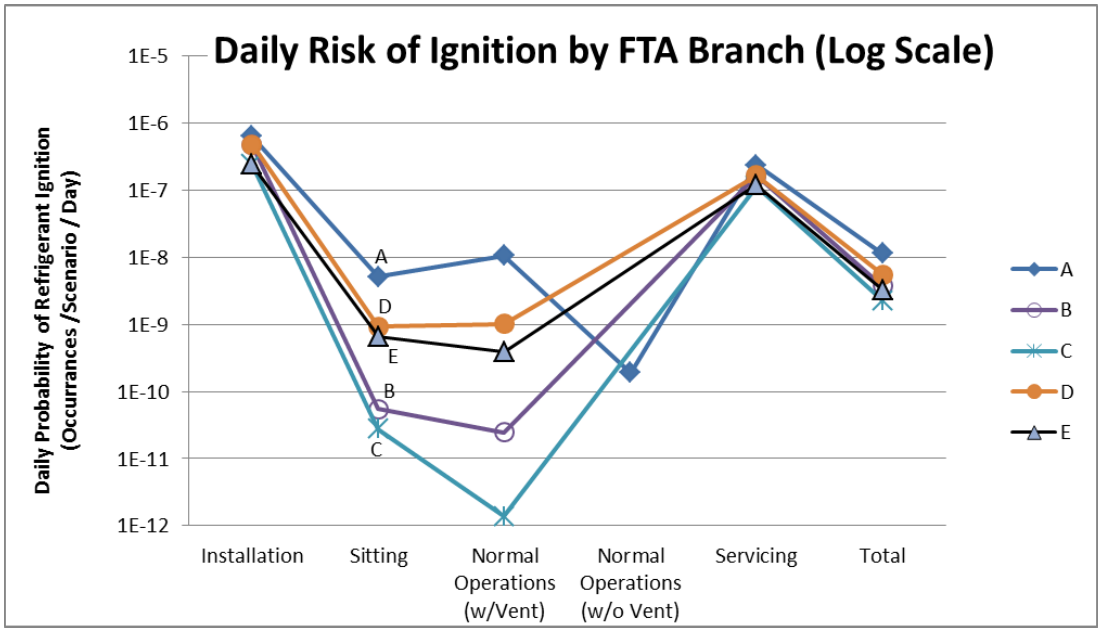


Figure 5-1. Comprehensive FTA Risk Analysis Results

5.2 *Sensitivity Results*

Based on feedback from the PMS, Navigant conducted a limited sensitivity analysis around specific parameters in the fault trees, to understand the relative impact of specific branches of the tree and specific inputs. The team evaluated sensitivities for three sets of inputs, (1) ventilation and leak detection, (2) number of chillers in a mechanical room, and (3) the percentage of leaks that are large.

5.2.1 Ventilation and Leak Detection

The Figure 5-2 shows the fault tree branch that pertains to ventilation and leak detection for scenario A. Based on FTA event combination rules discussed in Section 3.1, above, the chiller self-diagnosis capabilities and refrigerant monitor functionality carry equal weight, meaning that a change in probability by the same magnitude for either event will cause the same resulting change in combined probability.

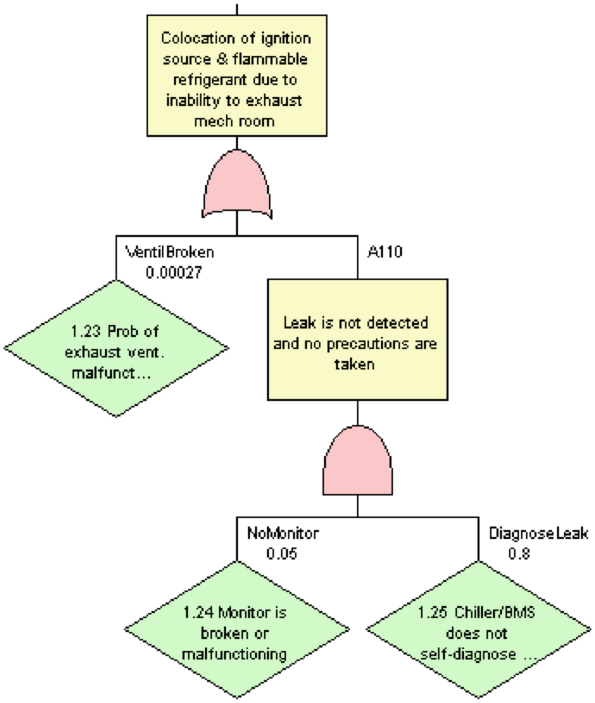


Figure 5-2. Example Fault Tree Branch for Ventilation and Leak Detection from Scenario A

Table 5-3 shows the results of our sensitivity analysis regarding the reliability of ventilation and leak detection equipment in scenario A. The reduction in risk of either chiller self-diagnosis or refrigerant monitor reliability by approximately 75% produces a similar reduction of 53% in total risk. A reduction in risk for both factors reduces total risk by 62%. However, ventilation reliability improvements result in smaller reductions in risk. Because the ventilation failure risk is under an OR gate, the impact is significantly diminished relative to the leak detection variables. Further, the probability of ventilation failure is several orders of magnitude smaller than combined risk of monitor malfunction and failure to self-diagnose.

Table 5-3. Sensitivity Analysis Results (Probabilities) for Varying Ventilation and Leak Detection Input Probabilities

(Number of Altered Variables) Altered Variable Names	FTA Inputs (Those that differ from baseline are in **bold** font)			Change in Ignition Risk
	Ventilation Malfunction	No Chiller Self-Diagnosis	Monitor Malfunction	% Relative to Baseline
Baseline	2.7 E-4	0.8	0.05	Baseline
(1) Ventilation reliability	**2.7 E-5**	0.8	0.05	-2%
(1) Chiller self-diagnosis	2.7 E-4	**0.2**	0.05	-53%
(1) Monitor reliability	2.7 E-4	0.8	**0.01**	-53%
(2) Chiller self-diagnosis, monitor reliability	2.7 E-4	**0.2**	**0.01**	-62%
(2) Chiller self-diagnosis, ventilation reliability	**2.7 E-5**	**0.2**	0.05	-56%
(2) Monitor reliability, ventilation reliability	**2.7 E-5**	0.8	**0.01**	-56%
(3) Chiller self-diagnosis, monitor reliability, ventilation reliability	**2.7 E-5**	**0.2**	**0.01**	-64%

5.2.2 Number of Chillers

Table 5-4 shows the results of our sensitivity analysis regarding the number of chillers in mechanical rooms for scenario A, ranging from one to four chillers (baseline assumption is two). Results show that adding one additional chiller to the baseline increases the risk by approximately 47%.

Table 5-4. Sensitivity Analysis Results for Number of Chillers in Mechanical Room (Scenario A)

Number of Chillers in Mechanical Room	Change in Ignition Risk (% Relative to Baseline
1	-42%
2 (Baseline)	Baseline
3	47%
4	89%

5.2.3 Percentage of Leaks that are Large

As discussed in Section 4.2.3, above, technicians' estimates that 5% of leaks are large enough to produce flammable concentrations are anecdotal and imprecise. To understand the implications of variation on this estimate, we ran simulations on a range of values from 1% to 50% for Scenario A. This analysis looks only at the change in percentage for traditional operating leaks, not for leaks that are caused by accidents (e.g., a forklift coming into contact with the chiller during construction). Results show that for a doubling in the percentage of leaks that are large (to 10% of all leaks), the total predicted risk increases by 73%, or 2.7 E-7. Interpolating the data shows that if approximately 13% of leaks are large, the predicted risk of ignition doubles.

Table 5-5. Sensitivity Analysis Results for Percent of Leaks that are Large (Scenario A)

Percent of Leaks that are Large	Change in Ignition Risk (% Relative to Baseline
1%	-68%
5% (Baseline)	Baseline
10%	73%
25%	260%
50%	560%

6. Conclusions

6.1 *Ignition Risk*

The FTA results discussed in Section 1, above, represent conservative estimates of risk for each given scenario. As noted in Section 2.1, the analysis uses R-32 as the representative 2L refrigerant. All additional inputs to the fault tree analysis err on the conservative side to ensure that these results never underestimate the level of risk.

Given the breadth of variables involved in each scenario, identifying the level of impact of each variable is difficult. The findings below outline the observed trends and highlight the areas that introduce clear changes in the risk between scenarios.

6.2 *Overall Findings*

The risk for the mechanical room is half an order of magnitude greater than that of the rooftop scenarios, in which very little (if any) refrigerant can build up into a flammable concentration. In fact, for normal operation, rooftops have the lowest risk of all of the scenarios, regardless of size or leak frequency.

For all scenarios, predicted risks are greatest during installation, followed closely by servicing. The increased risk relative to other scenarios is due to the addition of new ignition sources (e.g., welders and other spark-generating tools) introduced by people in close proximity to the chiller. Further, risk increases due to the added potential for leaks due to accidents. During installation and commissioning, unlike servicing, it is less likely that a technician would need to engage in higher-risk repair procedures, such as replacing pipes.

The risk during those activities is one or more orders of magnitude greater than during normal operation, due to the added presence of ignition sources associated with technician equipment.

However, on an annual basis, normal operations pose a greater portion of risk since the normal operating state prevails for 98% of the year.

A reduction in the charge size (via smaller capacity or through the use of multi-circuit chillers) will reduce the risk of ignition, by limiting the amount of refrigerant that can accumulate in the space for a given leak.

6.3 *Mechanical Room*

The total predicted risk of scenario A is more than half an order of magnitude greater than the predicted risk for the Scenario C, the least risky scenario. The refrigerant leak monitors and exhaust ventilation systems are fundamental in preventing refrigerant build-up, but the potential for failure of either the monitoring system or the exhaust ventilation presents a significant risk for this indoor scenario

Based on the sensitivity analysis, the number of chillers used in the installation makes a significant impact on the risk, as evidenced by the sensitivity analysis on scenario A (Table 5-4, above). More units installed in the mechanical room present more opportunities for a leak and a greater chance for a technician to make an error.

The predicted risk during service and installation activities in mechanical rooms has only marginally greater predicted risk compared to that of performing those activities on rooftops, even though the chiller modeled in mechanical rooms has a much higher charge of refrigerant. This is due to the fact that safety mechanisms in the mechanical room negate much of the risk created by an increased presence of ignition sources and a greater quantity of refrigerant.

6.4 *Rooftop*

Rooftop scenarios all exhibited lower predicted risk than the mechanical room scenario, due to two factors:

- The lack of potential ignition sources in close proximity to the refrigerant (and inaccessibility by people, in most cases)
- The unlikeliness of forming flammable refrigerant concentrations due to rapid refrigerant dispersion

The 200 ton screw chiller scenarios with open airflow (B) and restricted airflow (D) had greater predicted risk than the 100 ton scroll chiller scenarios with open airflow and restricted airflow, respectively, by approximately one half of an order of magnitude.

The 100 ton scroll scenarios (C and E) exhibited the lowest predicted risk of all scenarios. Scenario B (200 ton screw), despite having unrestricted airflow, had greater predicted risk than the smaller scroll chiller scenarios. The 200 ton chiller's larger charge volume and greater leak frequency compared to the 100 ton scroll negated much of the risk reduction afforded by the increased airflow around the chiller.

6.5 *Sensitivity Analysis*

The results of the sensitivity analysis of three key drivers of risk are as follows:

- **Ventilation and leak detection** – A reduction in the likelihood of either chiller self-diagnosis (lower likelihood of the chiller or building management system identifying a leak) or refrigerant monitor reliability (greater likelihood of monitor failure) by approximately 75% produces a similar reduction of 53% in total risk. A reduction in risk for both factors reduces total risk by 62%. Improving reliability of safety systems and ensuring that precautions can be taken in the event of a leak are key drivers in the predicted risk of a system. Increased self-diagnosis capabilities may provide important assurances of reduced risk.
- **Number of chillers in a mechanical room** – Adding one additional chiller to the baseline (two identical chillers) increases the risk by approximately 47%, while removing one chiller from the baseline, so that only one is present, reduces the risk by 42%. Without additional detailed analysis of chiller sizes, it is unclear from this study whether the predicted risk would be lower to achieve the same cooling capacity using a single large chiller versus two smaller chillers.
- **Percentage of leaks that are large** – Results show that for a doubling in the percentage of leaks that are large (to 10% of all leaks), the total predicted risk increases by 73%. Interpolating the data shows that if approximately 13% of leaks are large, the predicted risk of ignition doubles.

Additional understanding into the nature of refrigerant leaks, including frequency, total loss, and rate of loss would help refine predicted risk results.

6.6 *Comparison to Known Risk Levels*

Table 6-1 shows the risks predicted by the FTA in comparison to other safety hazard risks. Because the FTA results span more than three orders of magnitude, the scenarios generally are comparable to very different risks. The table includes the risks for four each scenario, as well as the risks for nine other activities.

Table 6-1. Safety Hazard Risk (Annual Frequency) Levels for Various Activities

	Safety Hazard Risk	Risk
	Fatal injury risk for worker in the mining industry[12]	2.0 E-4
	Occupant fatality risk in traffic crash (per person in U.S.)[13]	8.8 E-5
	Fatal injury risk on the job for employed people in the U.S.[14]	3.4 E-5
	Non-occupant fatality risk in traffic crash (per person in U.S.)[15]	1.6 E-5
	Injury risk for park attendee on amusement park ride[16]	4.4 E-6
	Annual refrigerant ignition risk in scenario A	**4.2 E-6**
	Frequency of ignition in residential heat pump using R-32[17]	3.7 E-6
Higher→	**Annual refrigerant ignition risk in scenario D**	**2.0 E-6**
	Annual refrigerant ignition risk in scenario B	**1.4 E-6**
	Annual refrigerant ignition risk in scenario E	**1.2 E-6**
	Annual refrigerant ignition risk in scenario C	**8.3 E-7**

---

[12] www.bls.gov/iif/oshwc/cfoi/worker_memorial.htm reports 19.8 fatalities in the Mining industry per 100,000 workers in 2010

[13] www-nrd.nhtsa.dot.gov/Pubs/811552.pdf reports 27,218 occupant fatalities in 2010 with a population of 309.3 million.

[14] www.bls.gov/iif/oshwc/cfoi/worker_memorial.htm reports 4,690 fatalities on the job in the U.S. in 2010 and 139,064,000 employed persons (from U.S. Census Bureau Table 620 from www.census.gov/compendia/statab/2012/tables/12s0620.pdf

[15] www-nrd.nhtsa.dot.gov/Pubs/811552.pdf reports 5,080 non-occupant fatalities in 2010 with a population of 309.3 million.

[16] www.nsc.org/news_resources/injury_and_death_statistics/Documents/Report%202010-Sep_2011_rev%2012%205%2011.pdf reports 4.4 injuries per million attendance – also reported as 0.7 injuries per million patron rides.

[17] Goetzler, et. al., "Risk Assessment of HFC-32 and HFC-32/134a (30/70 wt. %) in Split System Residential Heat Pumps," (1998); average of grand total frequencies across each region in Table 6-1. The table states that these data represent risk for a fire; however, the supporting text implies that these are the risk for ignition, not fire.

6.7 Mitigation Strategies

The results highlight opportunities for risk mitigation of two primary types: design practices and codes and standards. Both types of risk mitigation can be used for (most of) the following risk areas, which are (listed in no particular order):

- **Compressor type** – Manufacturer warranty data show that scroll chillers exhibit lower leak frequencies than screw chillers. Use of scroll compressors on 2L chillers will reduce the ignition risk by reducing the leak risk.
- **Multi-circuit chillers** – By utilizing multiple circuits, manufacturers prevent total loss of refrigerant in the event of a leak. Multi-circuit chillers will reduce the probability of creating and maintaining a flammable concentration of refrigerant.
- **Self-diagnosis capabilities** – Improvements in chiller self-diagnosis capabilities will provide redundancy to the refrigerant monitor. This will help to ensure that the building management system – the ventilation system in particular – can respond promptly in the case of a leak.
- **Safety equipment** – By increasing the use and reliability of additional safety equipment (e.g., refrigerant monitors), installers could use chillers with larger charge sizes without increasing the risk. An easy first step could be to drive design improvements in refrigerant monitor reliability. Users can also ensure greater reliability through regular calibration and testing.
- **Air circulation** – Exhaust ventilation plays a primary role in reducing risk. Codes that require exhaust ventilation in rooms with indoor 2L chillers could enable much safer operation.
- **Outdoor (air-cooled) chillers** – Similar to the use of exhaust ventilation, outdoor operation eliminates much of the risk of flammable refrigerant accumulation, and simultaneously eliminates many of the ignition sources which are only present indoors.
- **Technician training** – The presence of technicians, both those working on the chiller, as well as any other personnel who may be working nearby, is a key concern, especially during installation and commissioning. Enhanced training programs, including explicit training on flammable refrigerants will reduce human-error-induced risk.
- **Exhaust ventilation reliability** – The exhaust-stage ventilation, by design, prevents build-up of flammable refrigerant concentrations. Any exhaust-stage ventilation downtime creates an opportunity for a potential leak to build to dangerous levels.

6.8 Future Work

This study provided valuable insights into the ignition risk of 2L refrigerants. The evaluation team identified three areas for future work which could lead to more detailed scientific understanding of the ignition risks, including:

- **Alternative refrigerants:** As discussed in Section 2.1, this study uses R-32 as the representative for all 2L refrigerants. Future studies on other refrigerants could provide insights into the risk sensitivity associated with flammability limits and other flammability characteristics of 2L refrigerants.

- **Extended research on key risk probabilities**: In the high-risk branches of the fault trees, the FTA results could be refined through additional research on each input variable. The data we use in this study are the best currently available, but through additional interviews with subject matter experts and scientific study of ignition sources and equipment failures, the FTA could be refined to reduce uncertainty.
- **Sensitivity analysis:** Sensitivity analysis can provide insights into the improvements in risk that might be achieved using the mitigation strategies discussed in Section 6.7. Sensitivity analysis could also be used to increase understanding of the impact of specific input variables on ignition risk. This could help in identification of additional mitigation strategies; understanding of probability targets for future R&D; and recommendations for safer building codes.

Appendix A. Flammable Concentration Modeling

The team conducted simulation and modeling of the refrigerant concentration that could develop as a result of a refrigerant leak in each of the five chiller scenarios outlined in the SOW. The model we developed used estimates of the size of the confined space, the ventilation present, and other factors, as well as the physical properties of the refrigerant and air, to calculate the concentration of refrigerant as a function of time in the area of analysis during and after a leak. We varied the leak rate (in lbm/hr), and ran separate simulations at each leak rate for each scenario to determine what leak rate would result in the longest duration of a concentration of refrigerant above the LFL.

The final result, plotted for each scenario, is the length of time in hours for which the concentration is above the LFL as a function of leak rate. The graphs of the results show two basic behaviors in the relation between concentration duration and leak rate. For all chiller types, some minimum leak rate is needed in order for a concentration above the LFL to develop; otherwise, the refrigerant is simply exhausted by the ventilation as it is leaked. For units where the relative charge of the chiller is small on the scale of the room size and ventilation rate, concentration duration generally rises with leak rate and then peaks at a level approximating a burst scenario. In this case, a high concentration develops in the room and persists above the LFL for some time as the room air is exhausted and mixed with fresh air until the concentration falls below the LFL. For larger chillers, another pattern is seen. In these cases, above the threshold value needed to attain the LFL, the time above LFL generally rises to a peak at a certain leak rate and then falls off. This is due to the fact that with larger charges, a constant amount of refrigerant can still be leaked which exceeds or equals that being removed by the ventilation, drawing out the duration above LFL. In these instances, very high leak rates simply increase the concentration in the room to a high level at a given time, but this concentration does not persist as long as with a slower leak.

The team selected the peak durations in each of the five chiller types for further modeling, as they represented the highest-risk scenarios. We used these results, combined with estimates of the likelihood of a sufficient ignition source becoming present during the period above the LFL, as the basis of the ignition probability values incorporated into the fault trees.
Figure B-1 through Figure B-5 show the results.

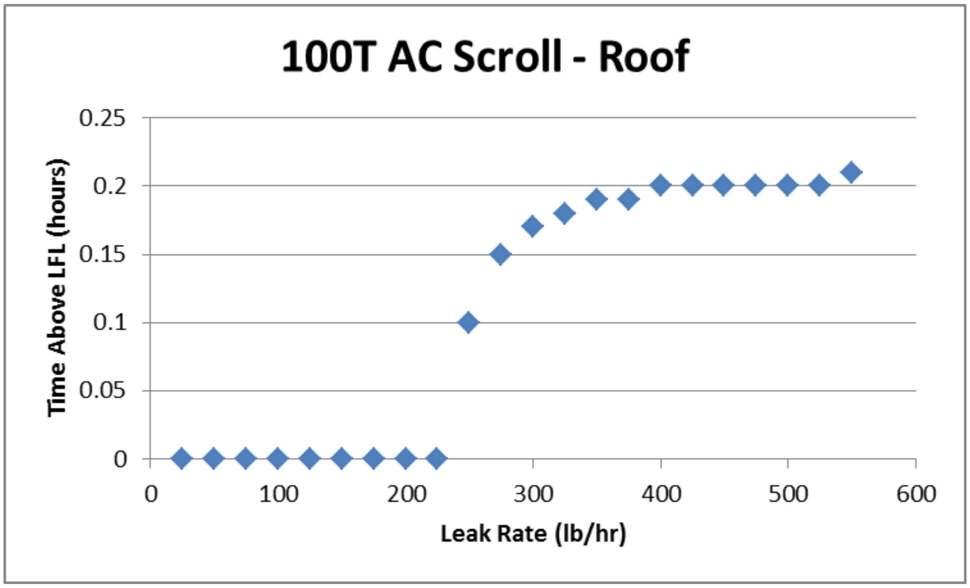


Figure A-1. Leak Rate versus Duration above LFL - 100T AC Scroll on an Airflow-Restricted Rooftop

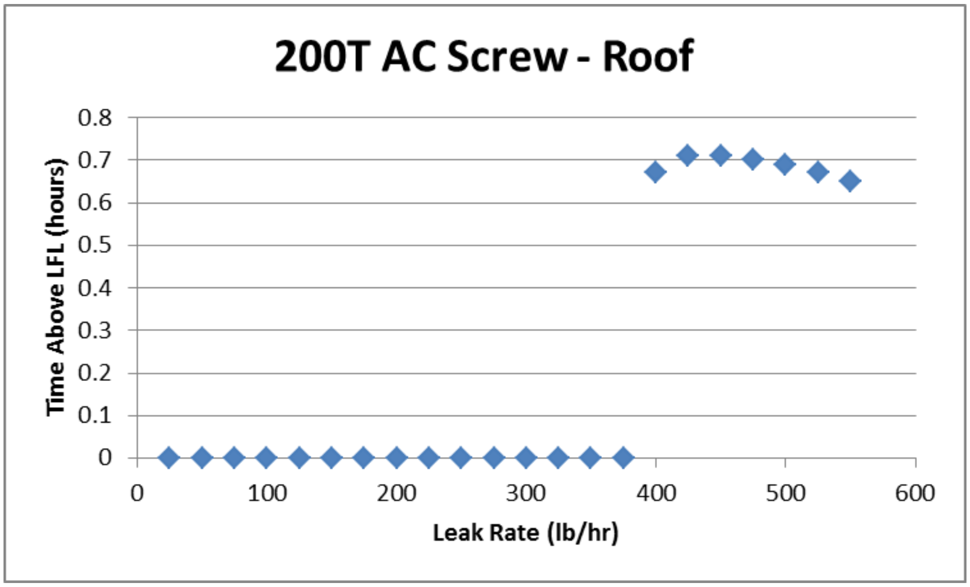


Figure A-2. Leak Rate versus Duration above LFL - 200T AC Screw on an Airflow-Restricted Rooftop

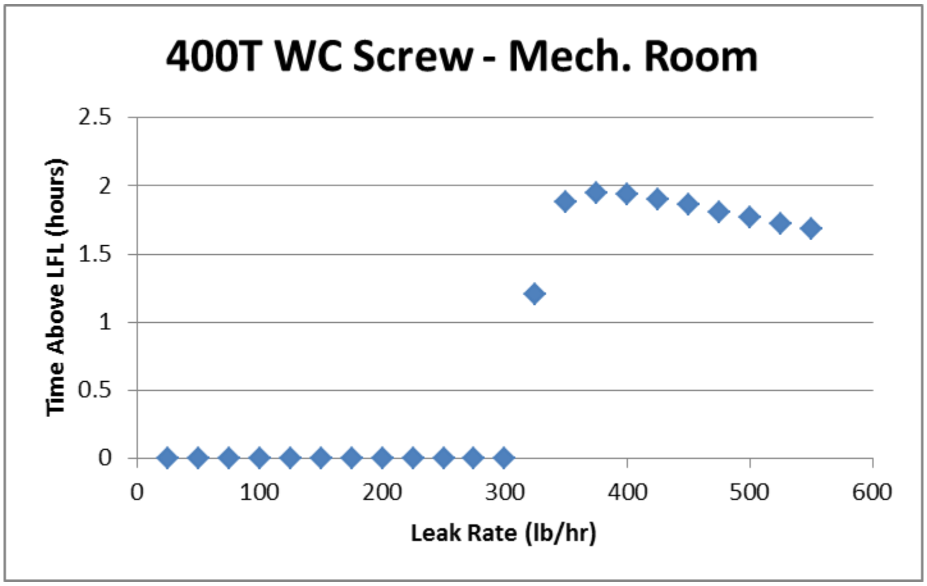


Figure A-3. Leak Rate versus Duration above LFL - 400T WC Screw in a Mechanical Room with no Functioning Exhaust Ventilation

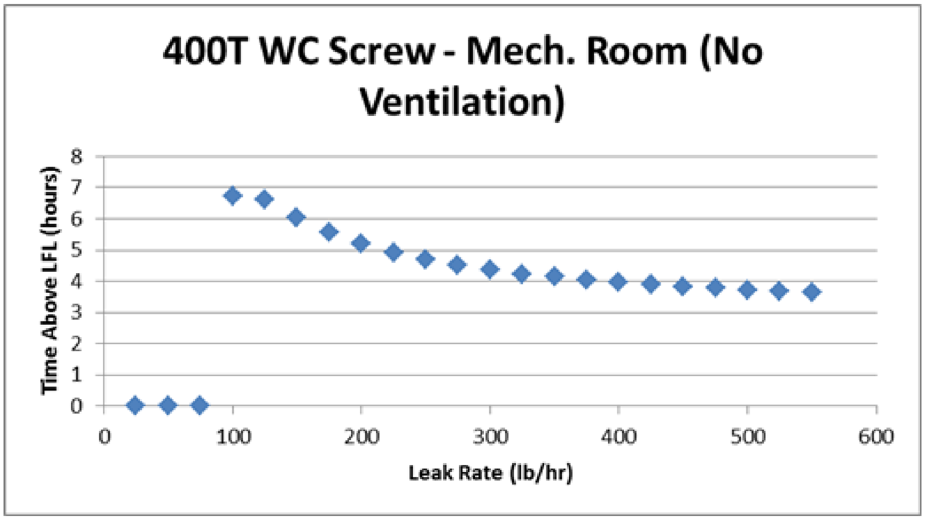


Figure A-4. Leak Rate versus Duration above LFL – 400T WC Screw in a Mechanical Room with no Ventilation

NAVIGANT

AHRI Project No. 8005:

Risk Assessment of Class 2L Refrigerants in Chiller Systems

Fault Trees and Fault Tree Input Details

Prepared for:

AHRI
AIR-CONDITIONING, HEATING,
& REFRIGERATION INSTITUTE

we make life better™

Prepared by:

Bill Goetzler
Matt Guernsey
Collin Weber

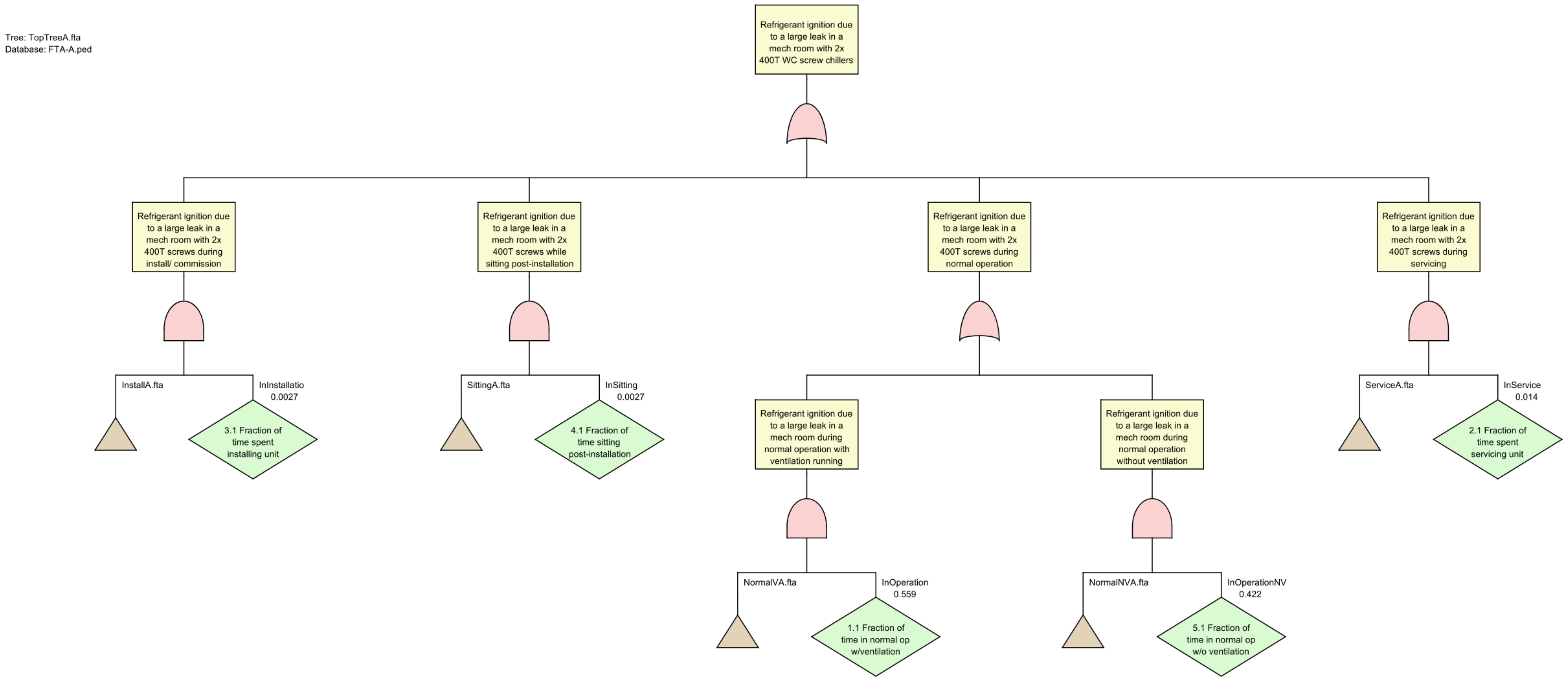
Navigant Consulting, Inc.
77 South Bedford St.
Suite 400
Burlington, MA 01803

781.270.0101
www.navigant.com

Final Report
July 2013

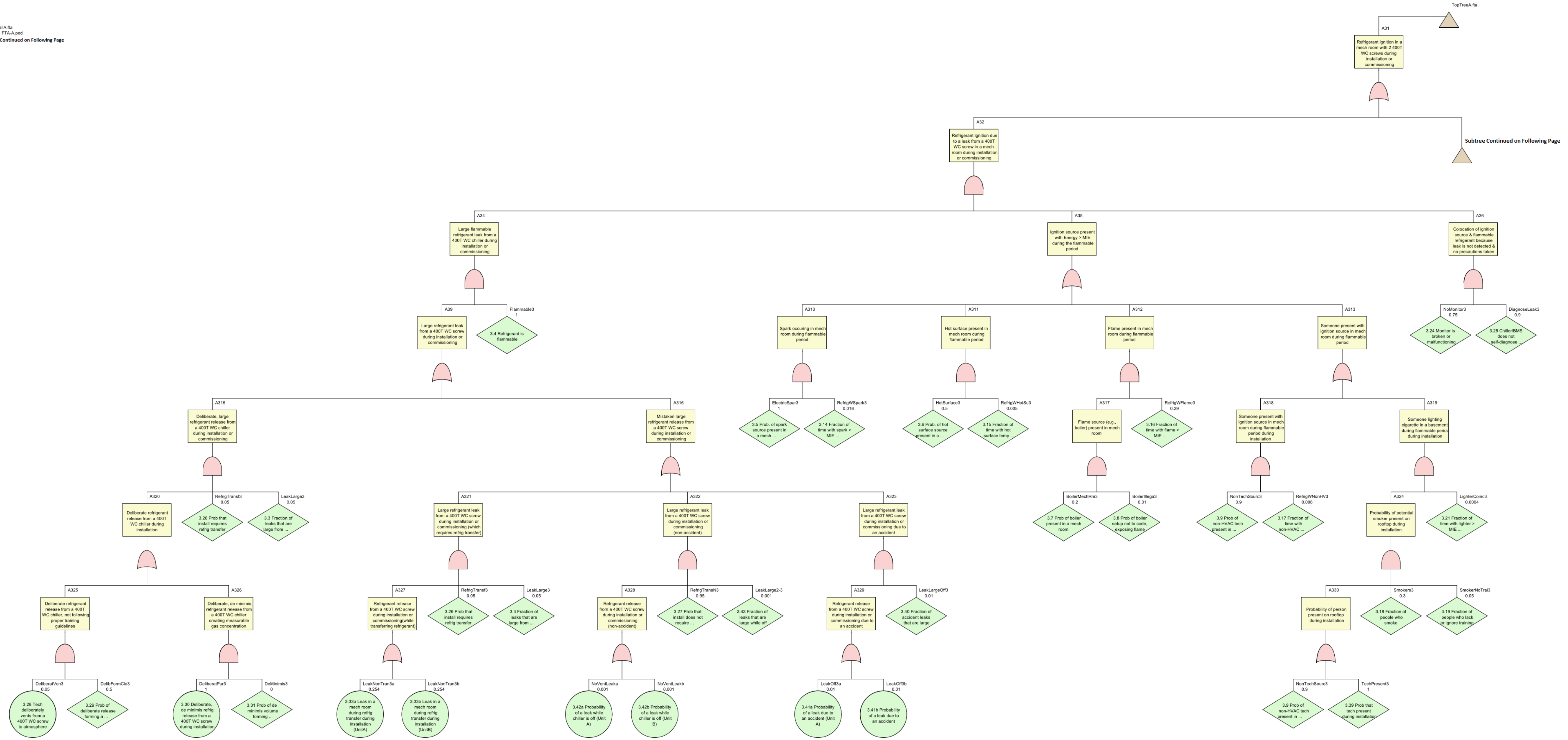
Table of Contents

Appendix A. Fault Trees – Scenario A

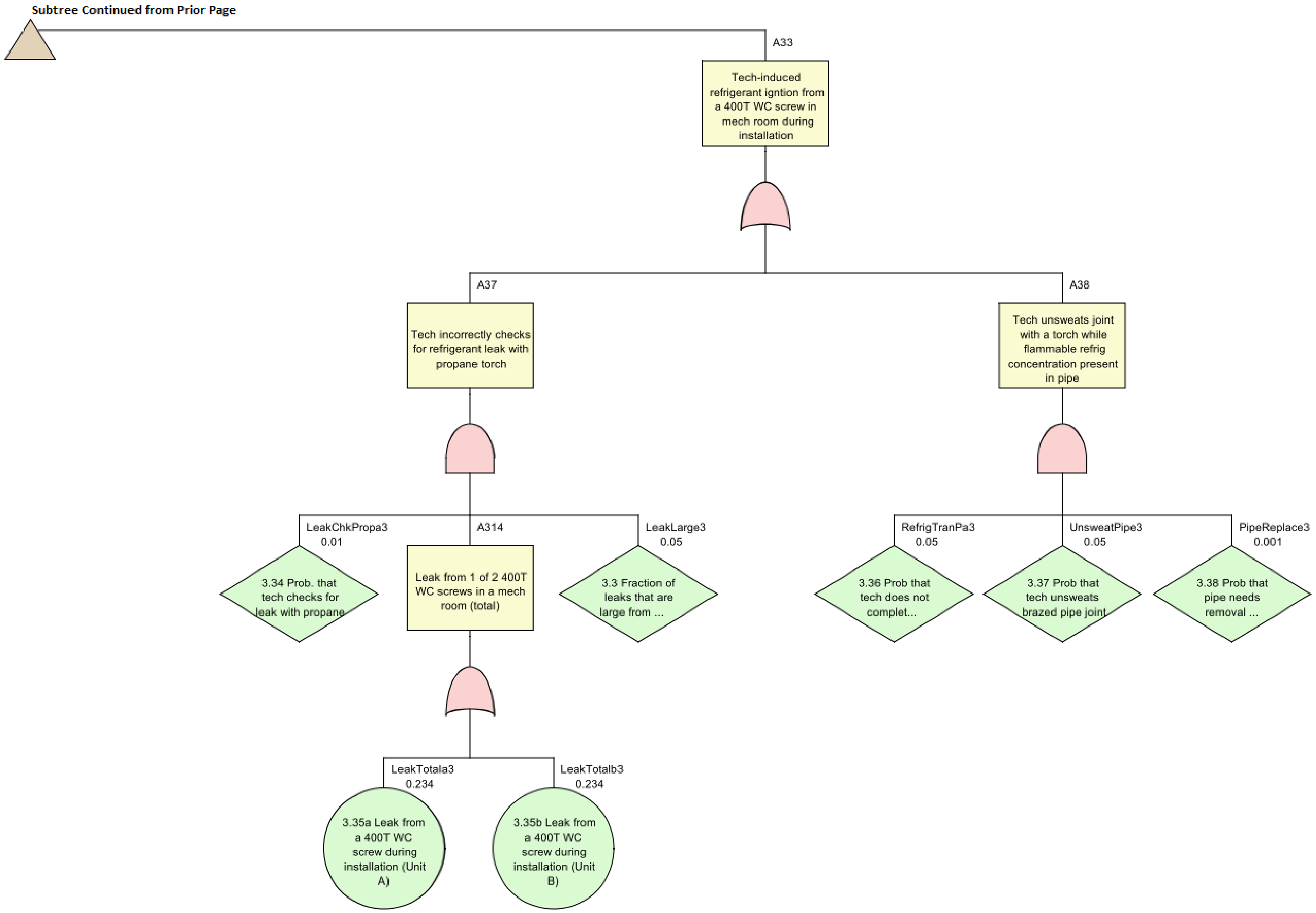


Tree: InstallA.fta
Database: FTA-A.ped

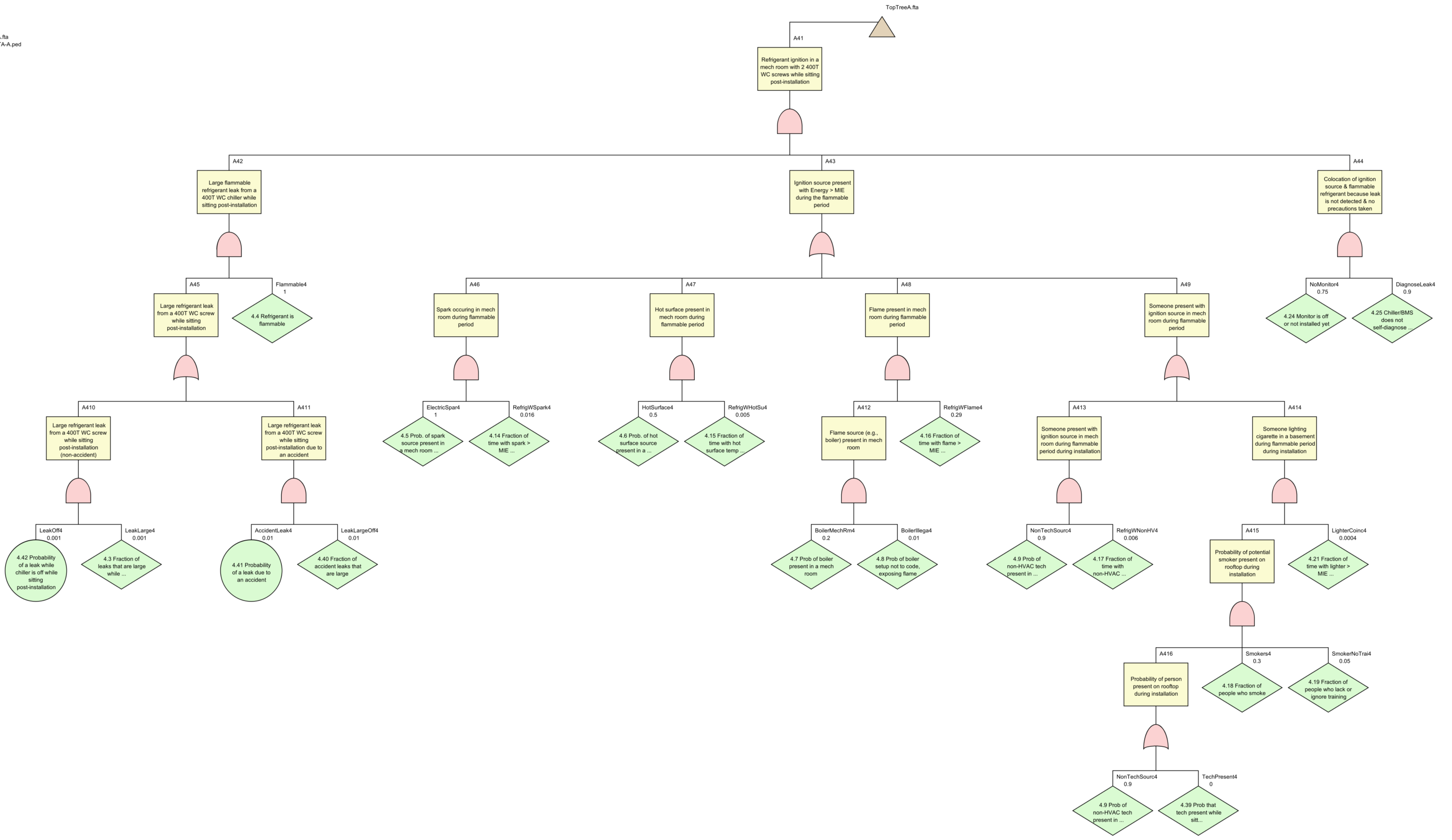
Subtree Continued on Following Page



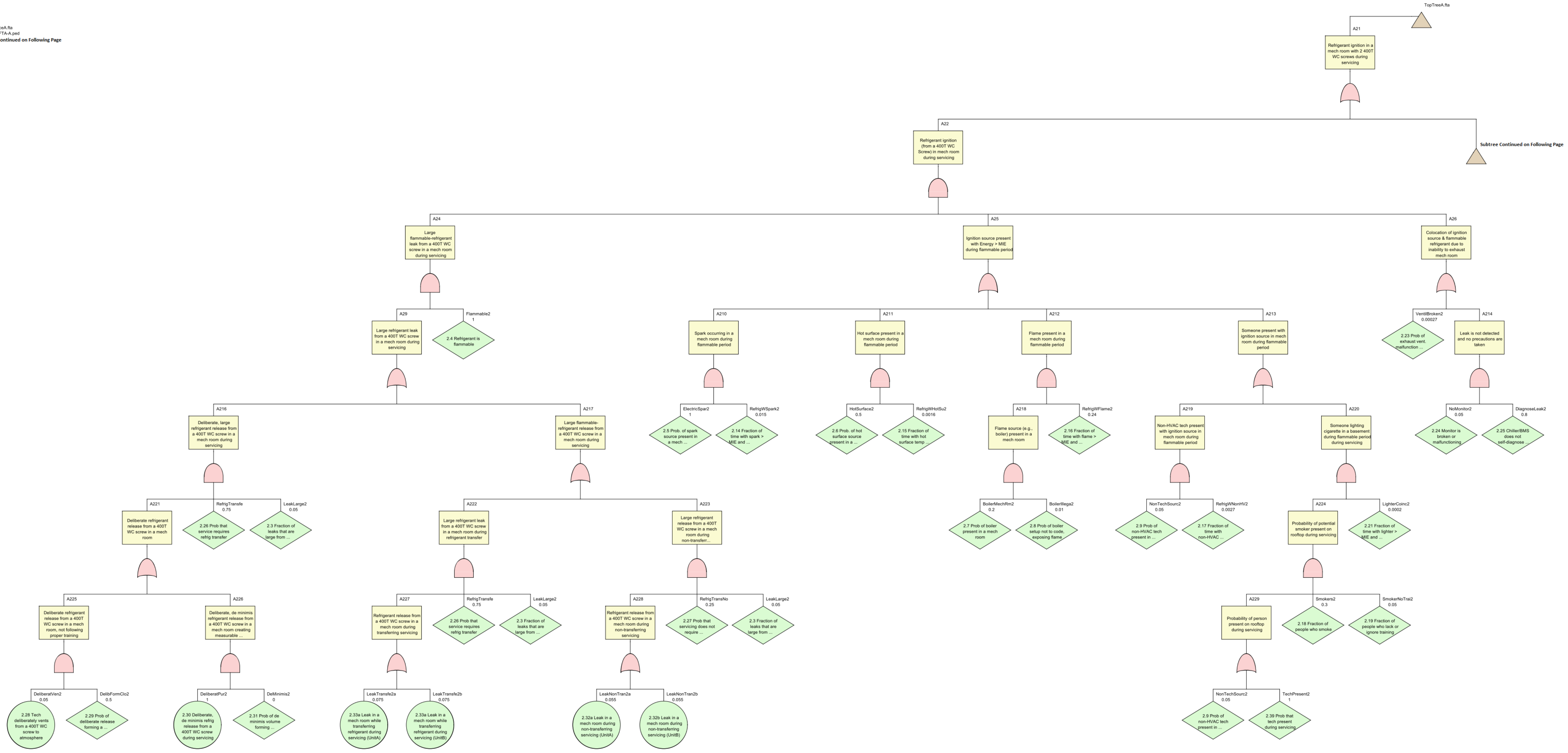
Tree: InstallA.fta
Database: FTA-A.ped
Subtree Continued from Prior Page



Tree: SittingA.fta
Database: FTA-A.ped

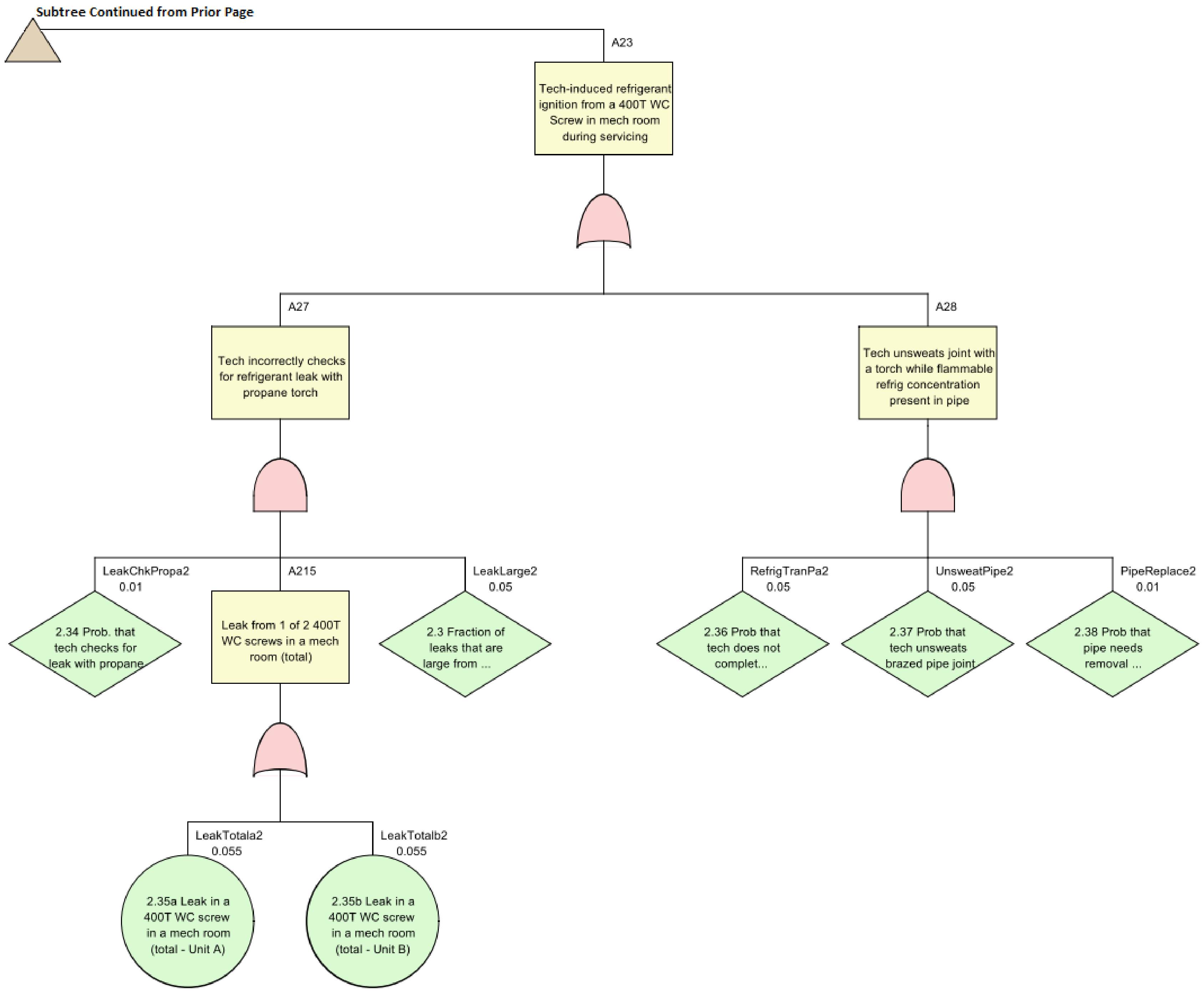


Tree: ServiceA.fta
Database: FTA-A.ped
Subtree Continued on Following Page

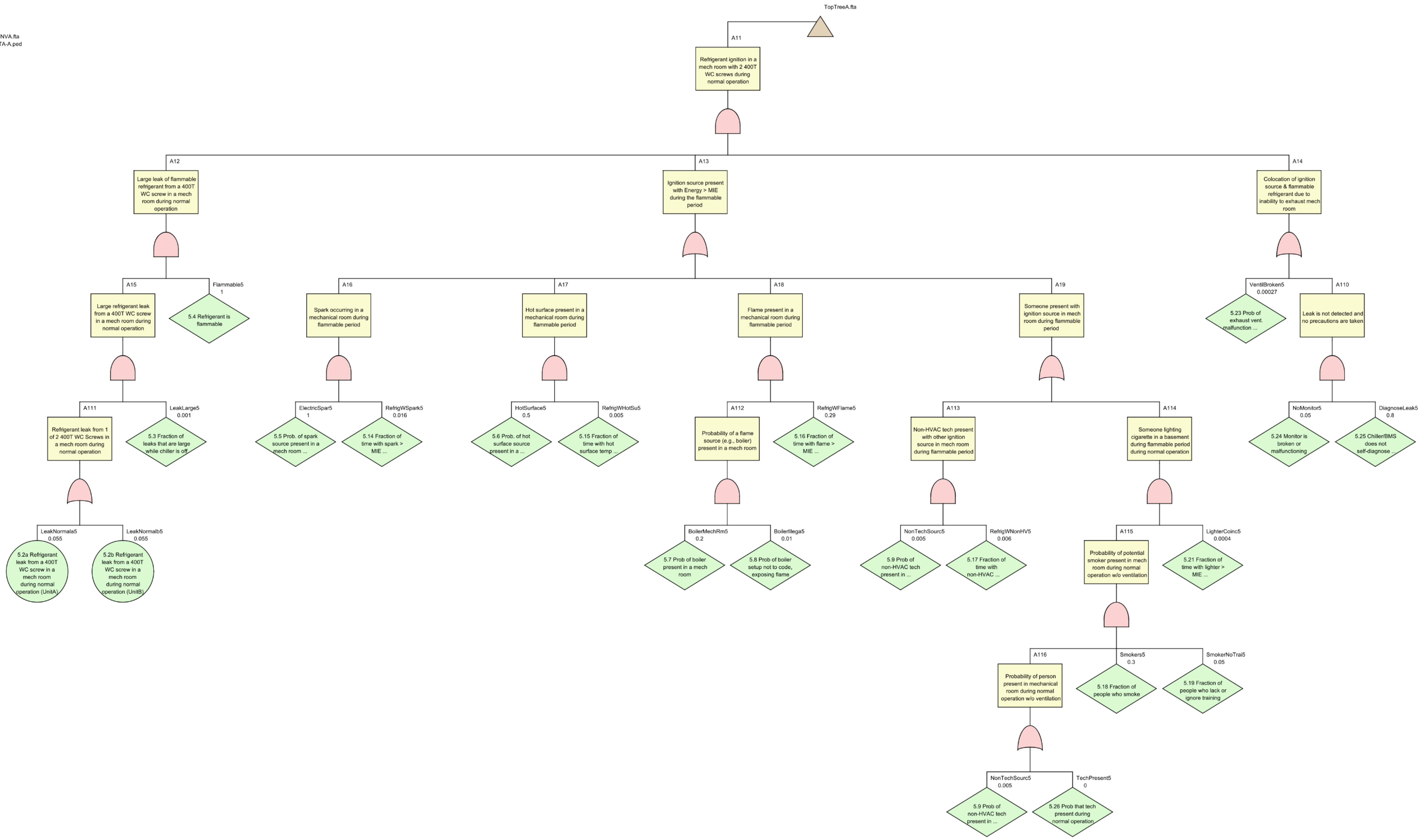


Tree: ServiceA.fta
Database: FTA-A.ped

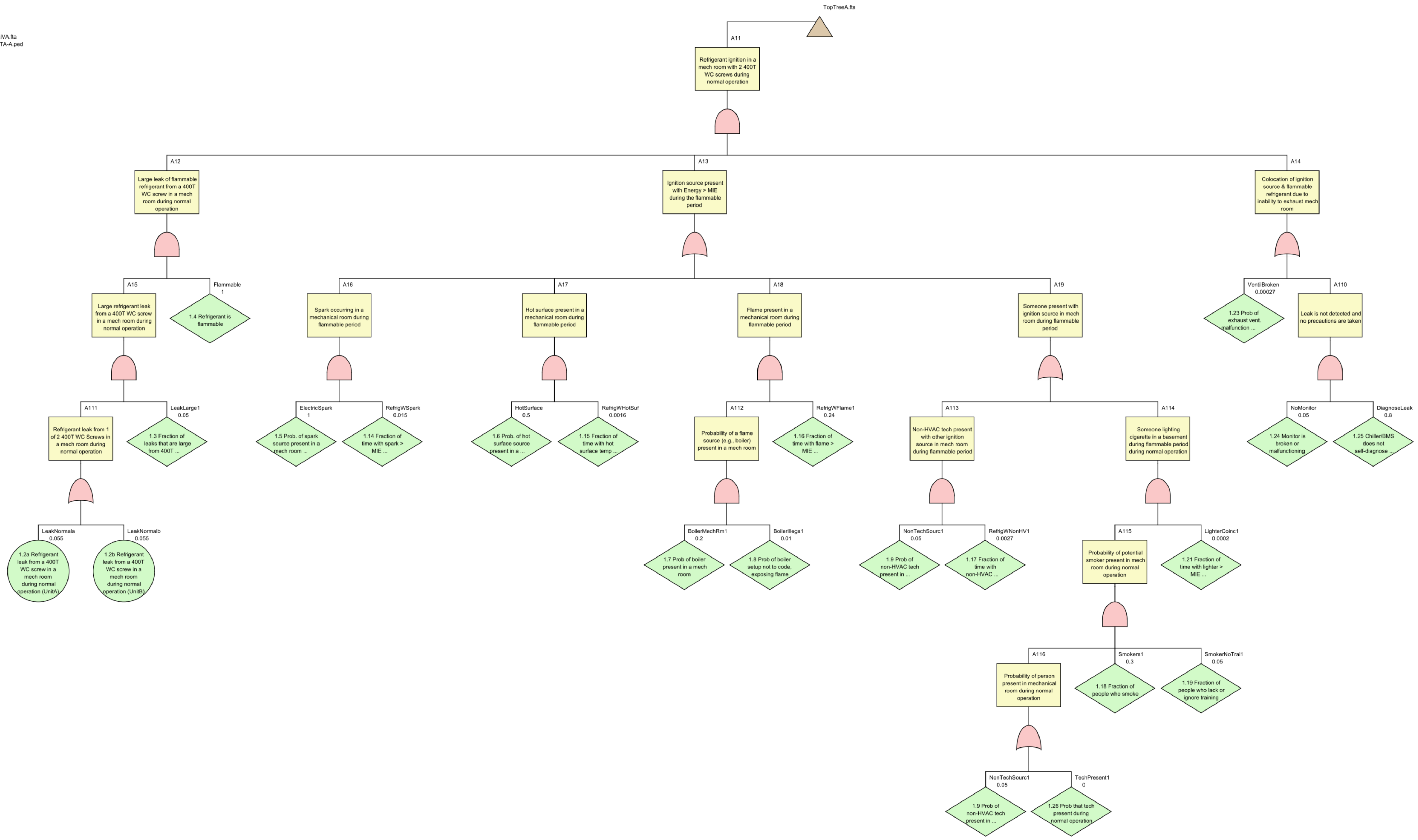
Subtree Continued from Prior Page



Tree: NormalNVA.fta
Database: FTA-A.ped

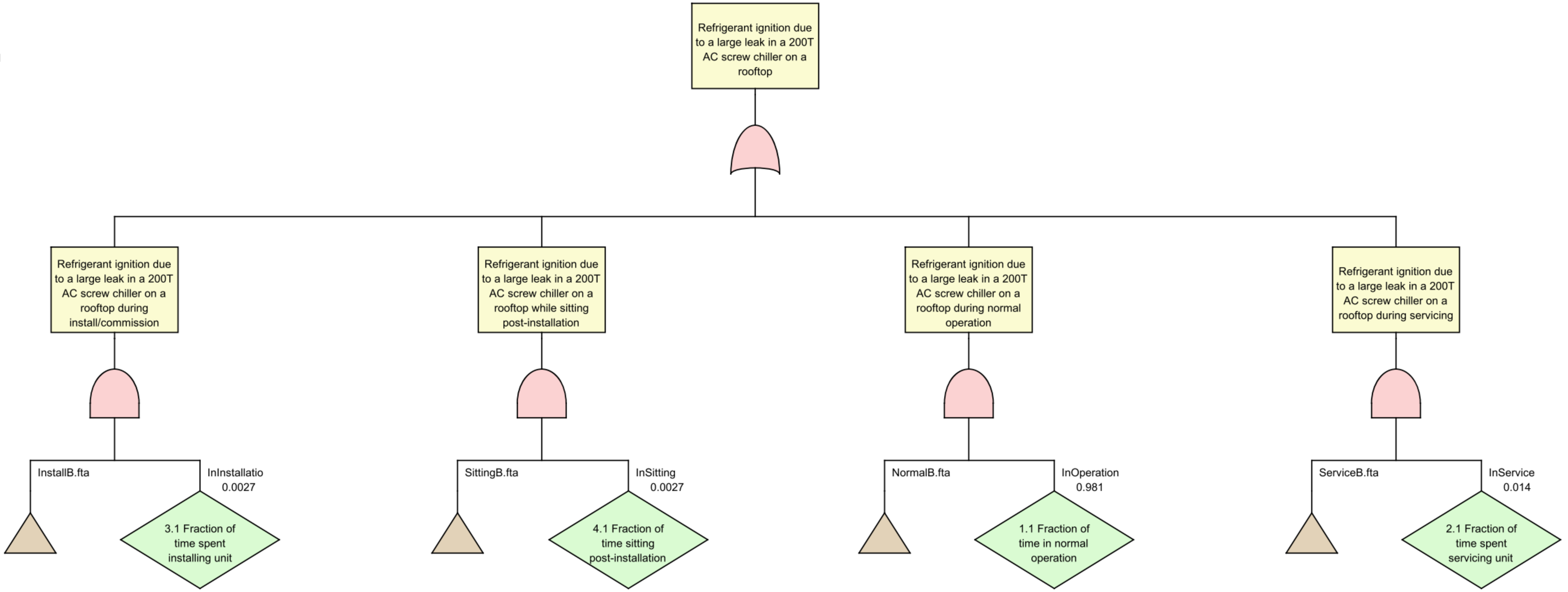


Tree: NormalVA.fta
Database: FTA-A.ped

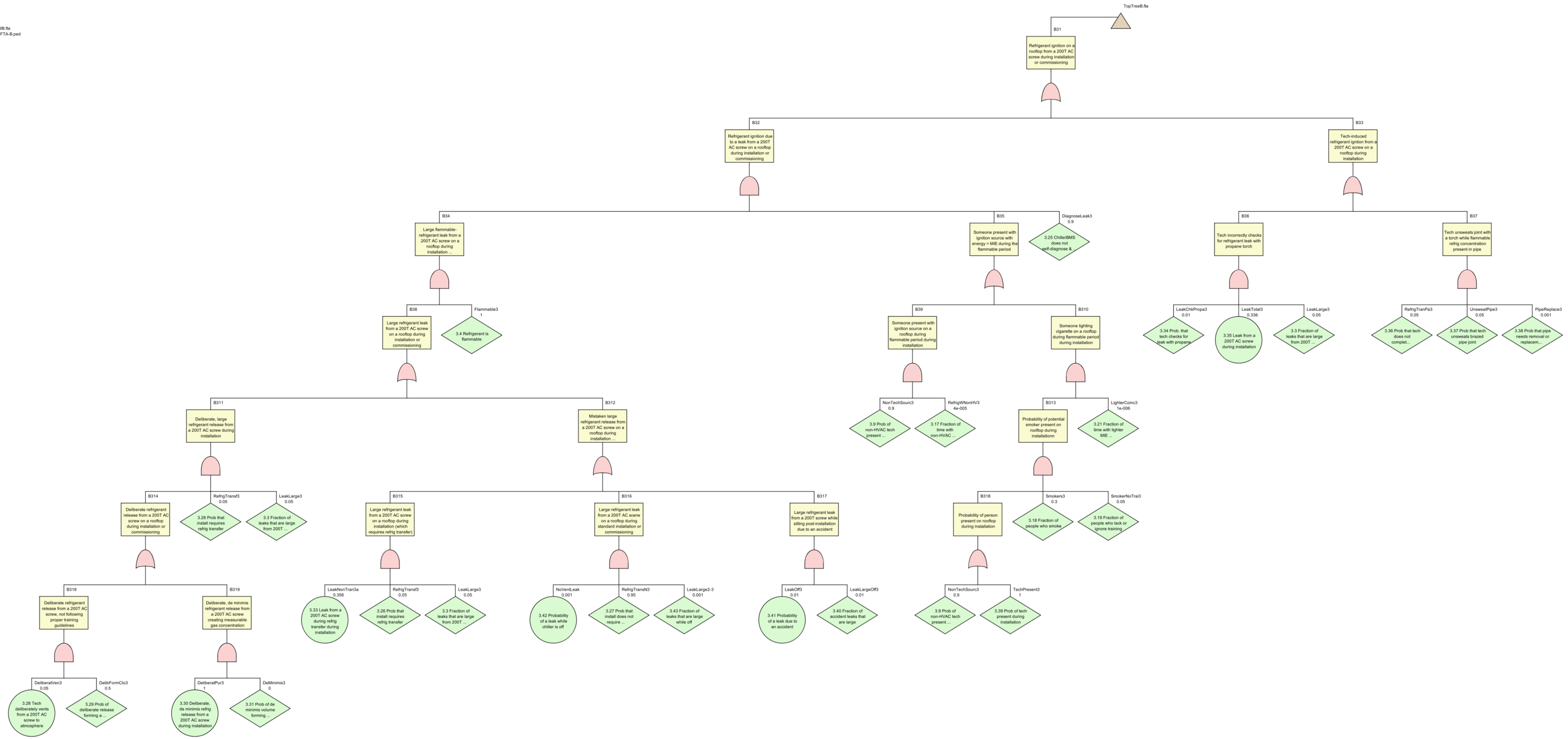


Appendix B. Fault Trees – Scenario B

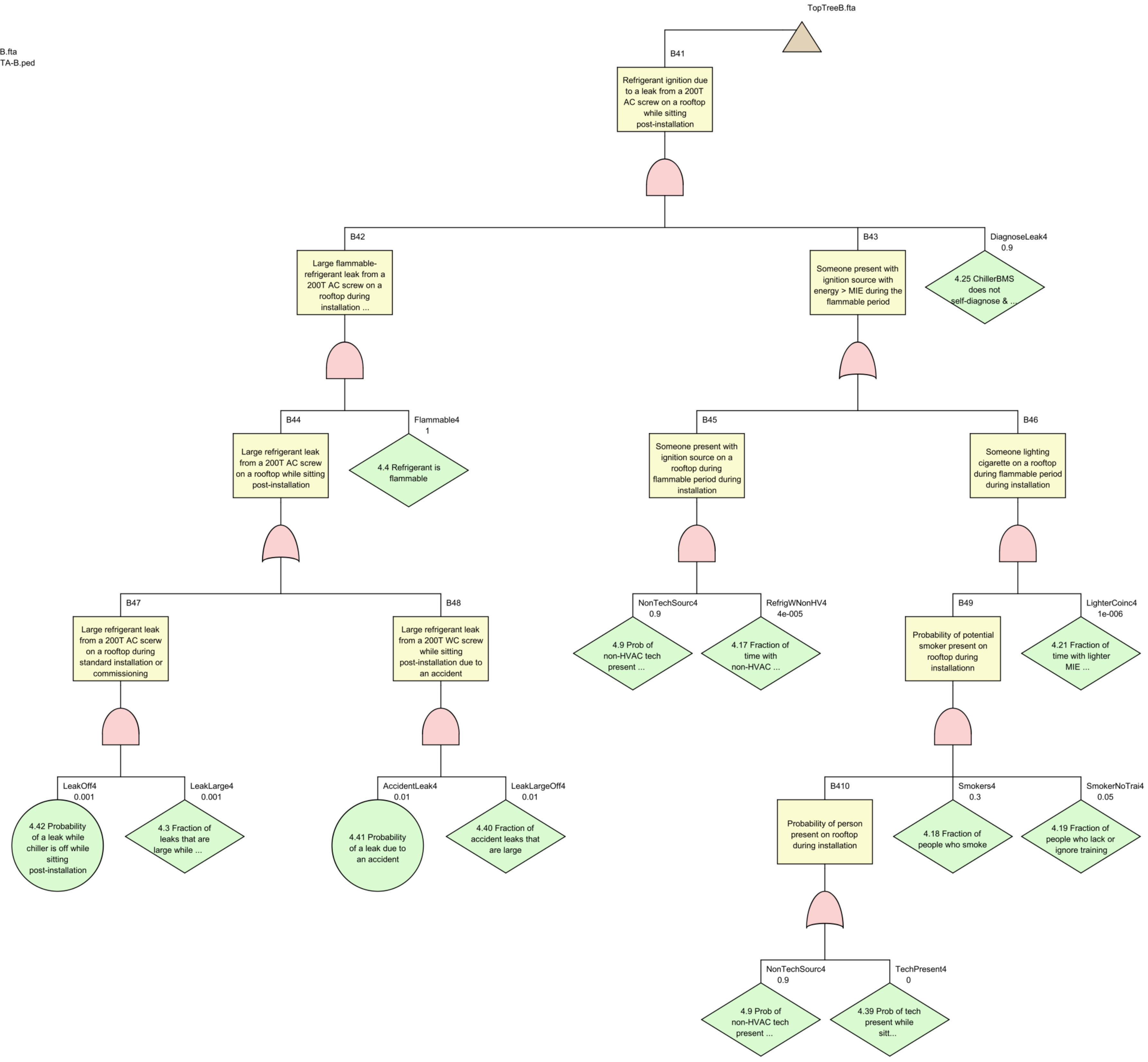
Tree: TopTreeB.fta
Database: FTA-B.ped



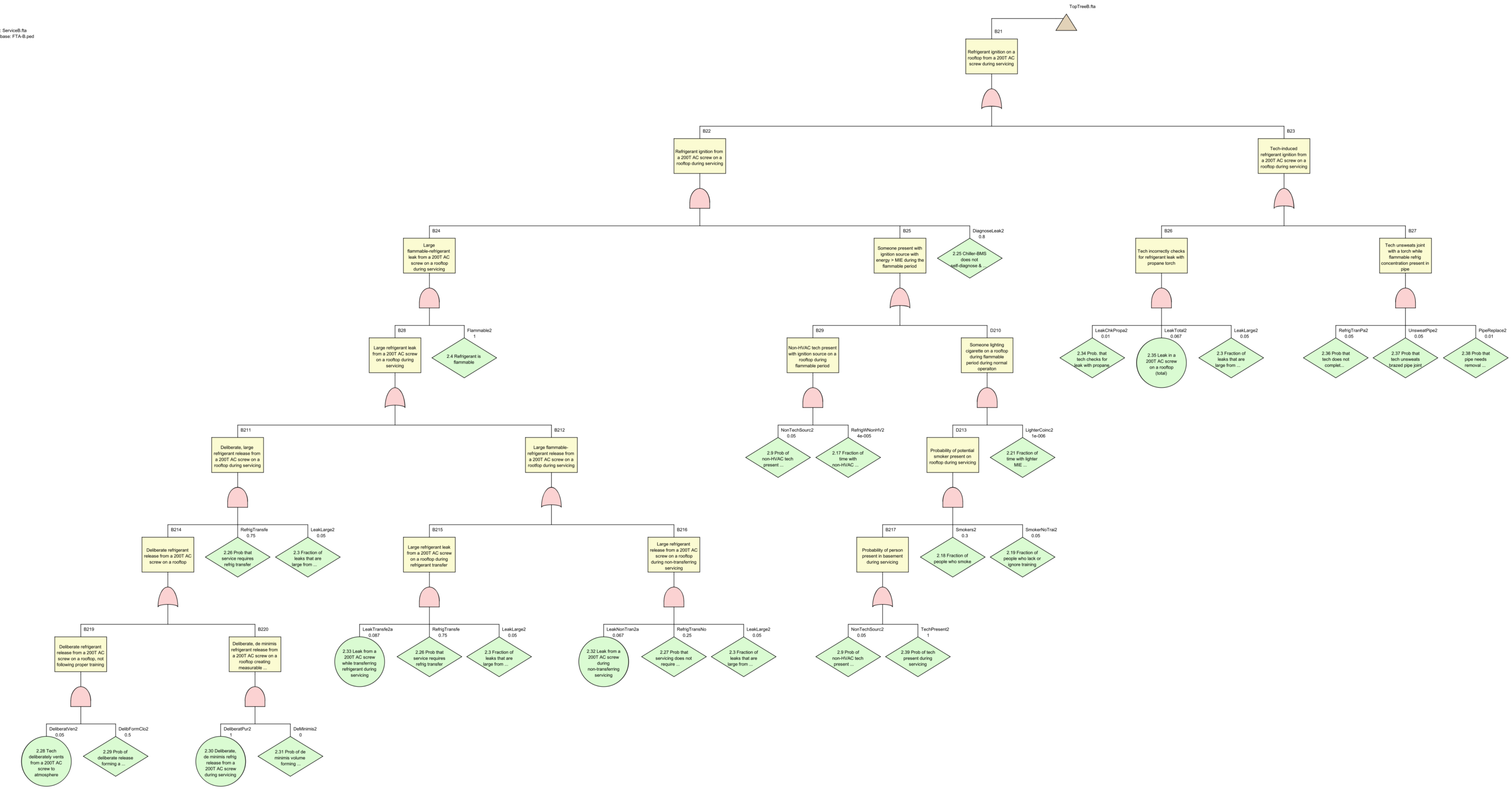
Tree: InstallB.fta
Database: FTA-B.ped

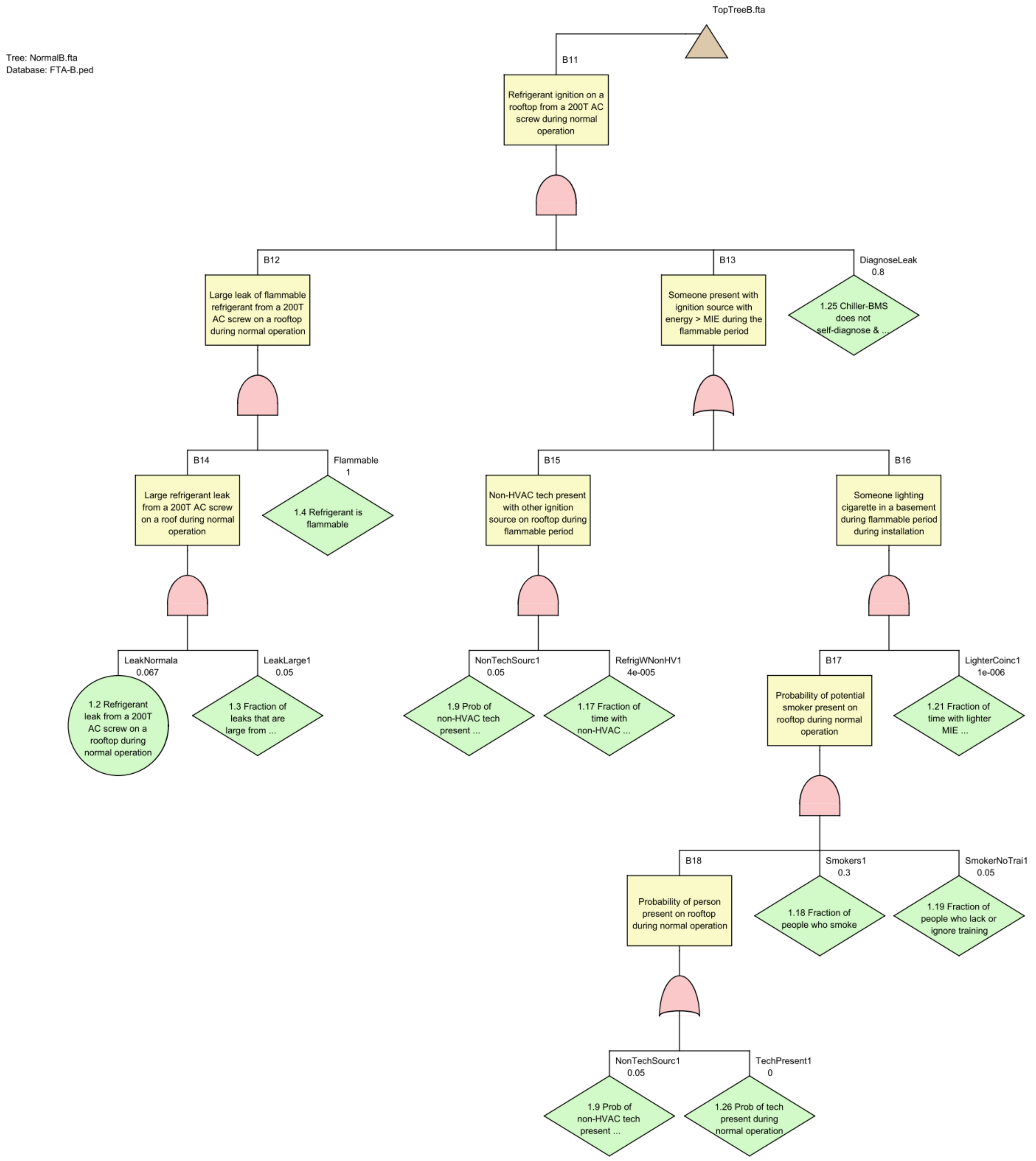


Tree: SittingB.fta
Database: FTA-B.ped

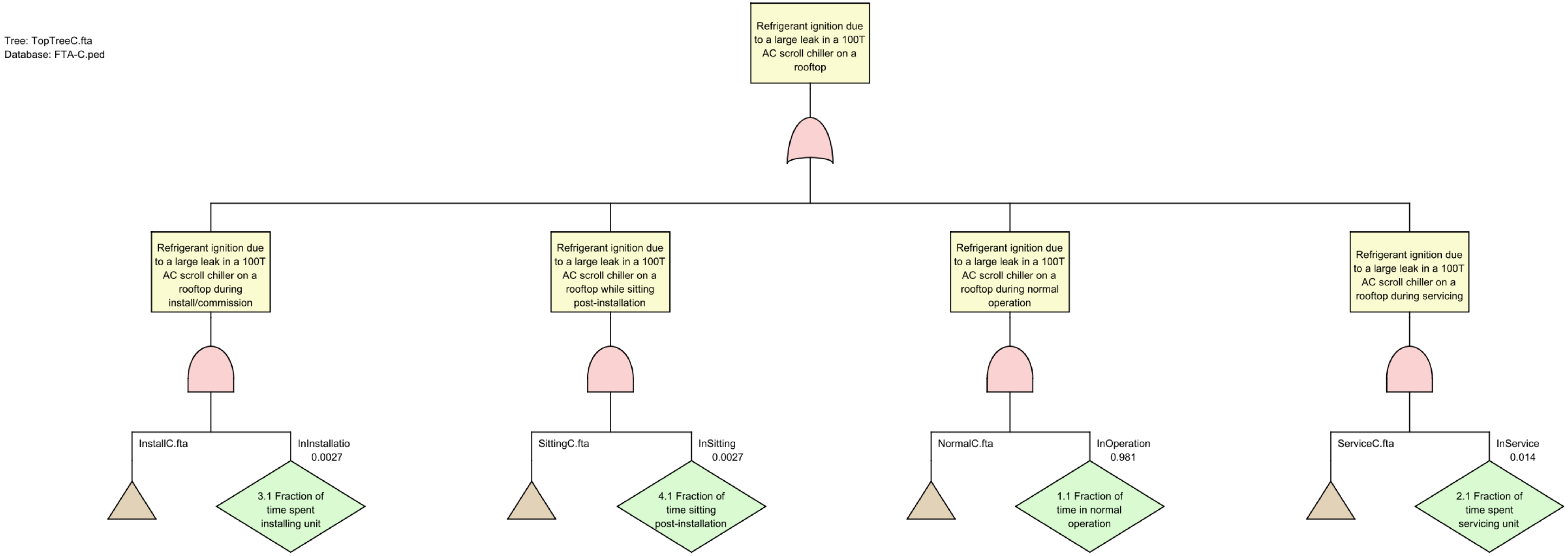


Tree: ServiceB.fta
Database: FTA-B.ped

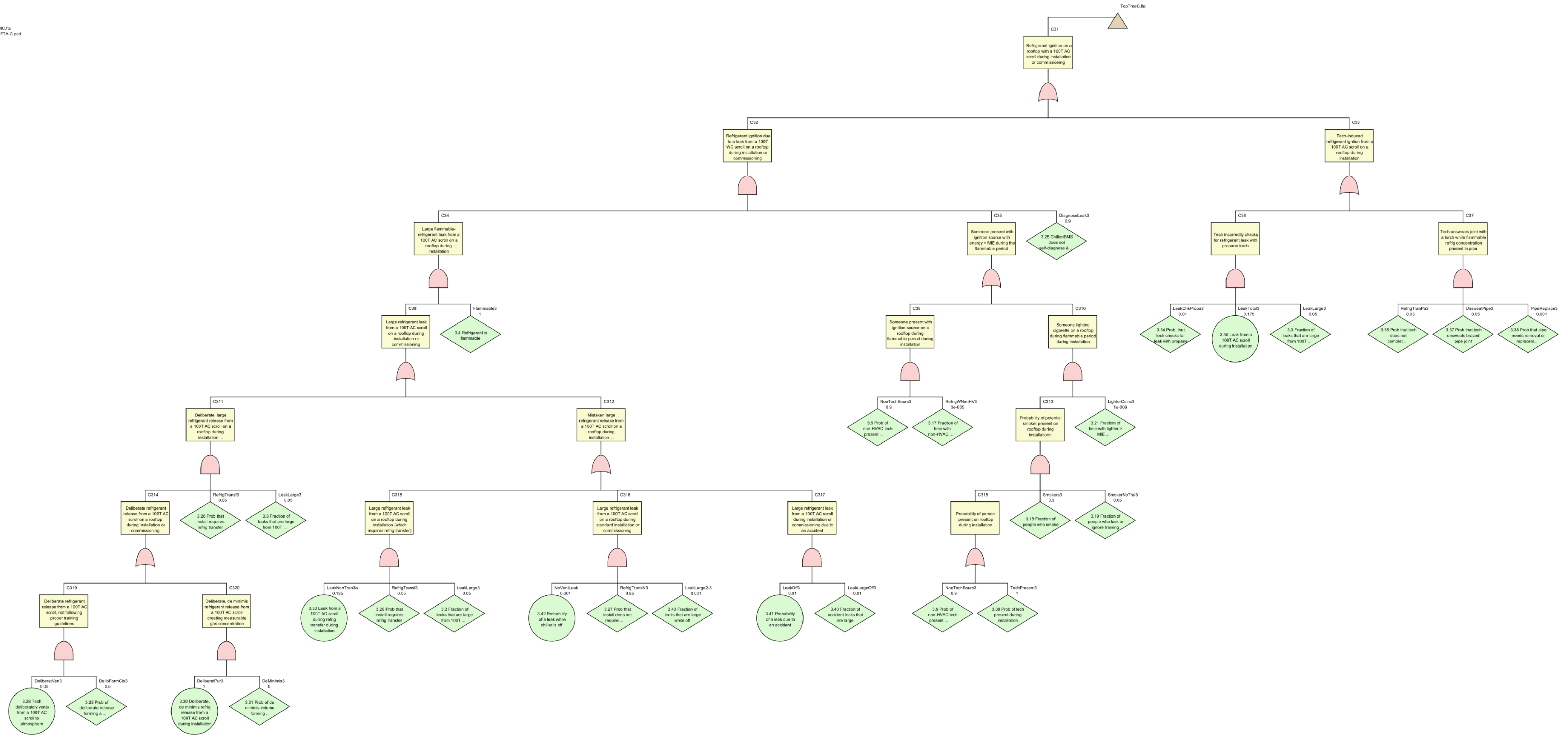


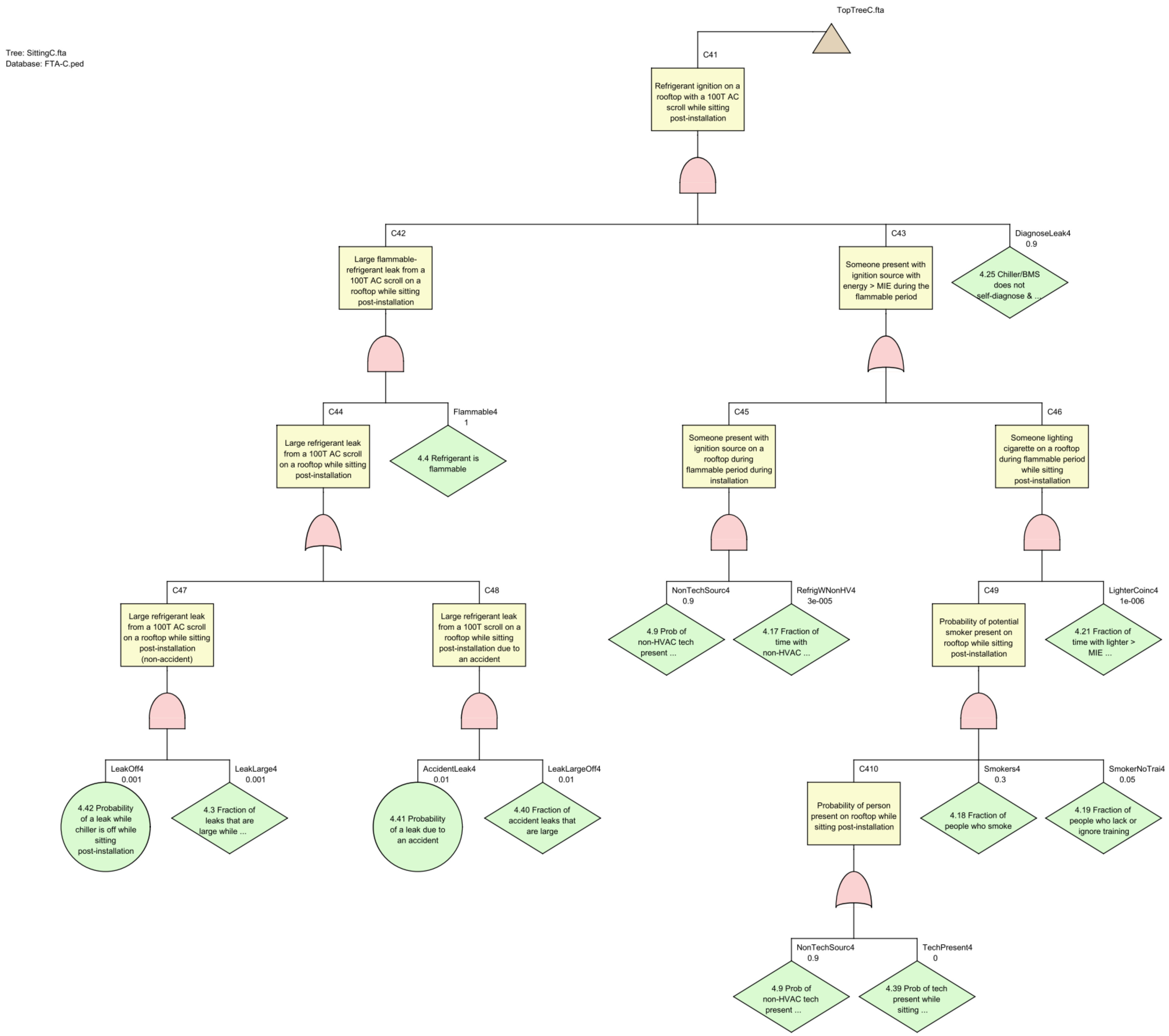

Tree: NormalB.fta
Database: FTA-B.ped
TopTreeB.fta
B11
Refrigerant ignition on a rooftop from a 200T AC screw during normal operation
B12
Large leak of flammable refrigerant from a 200T AC screw on a rooftop during normal operation
B13
Someone present with ignition source with energy > MIE during the flammable period
DiagnoseLeak
0.8
1.25 Chiller-BMS does not self-diagnose & ...
B14
Large refrigerant leak from a 200T AC screw on a roof during normal operation
Flammable
1
1.4 Refrigerant is flammable
B15
Non-HVAC tech present with other ignition source on rooftop during flammable period
B16
Someone lighting cigarette in a basement during flammable period during installation
LeakNormala
0.067
1.2 Refrigerant leak from a 200T AC screw on a rooftop during normal operation
LeakLarge1
0.05
1.3 Fraction of leaks that are large from ...
NonTechSourc1
0.05
1.9 Prob of non-HVAC tech present ...
RefrigWNonHV1
4e-005
1.17 Fraction of time with non-HVAC ...
B17
Probability of potential smoker present on rooftop during normal operation
LighterCoinc1
1e-006
1.21 Fraction of time with lighter MIE ...
B18
Probability of person present on rooftop during normal operation
Smokers1
0.3
1.18 Fraction of people who smoke
SmokerNoTrai1
0.05
1.19 Fraction of people who lack or ignore training
NonTechSourc1
0.05
1.9 Prob of non-HVAC tech present ...
TechPresent1
0
1.26 Prob of tech present during normal operation

Appendix C. Fault Trees – Scenario C

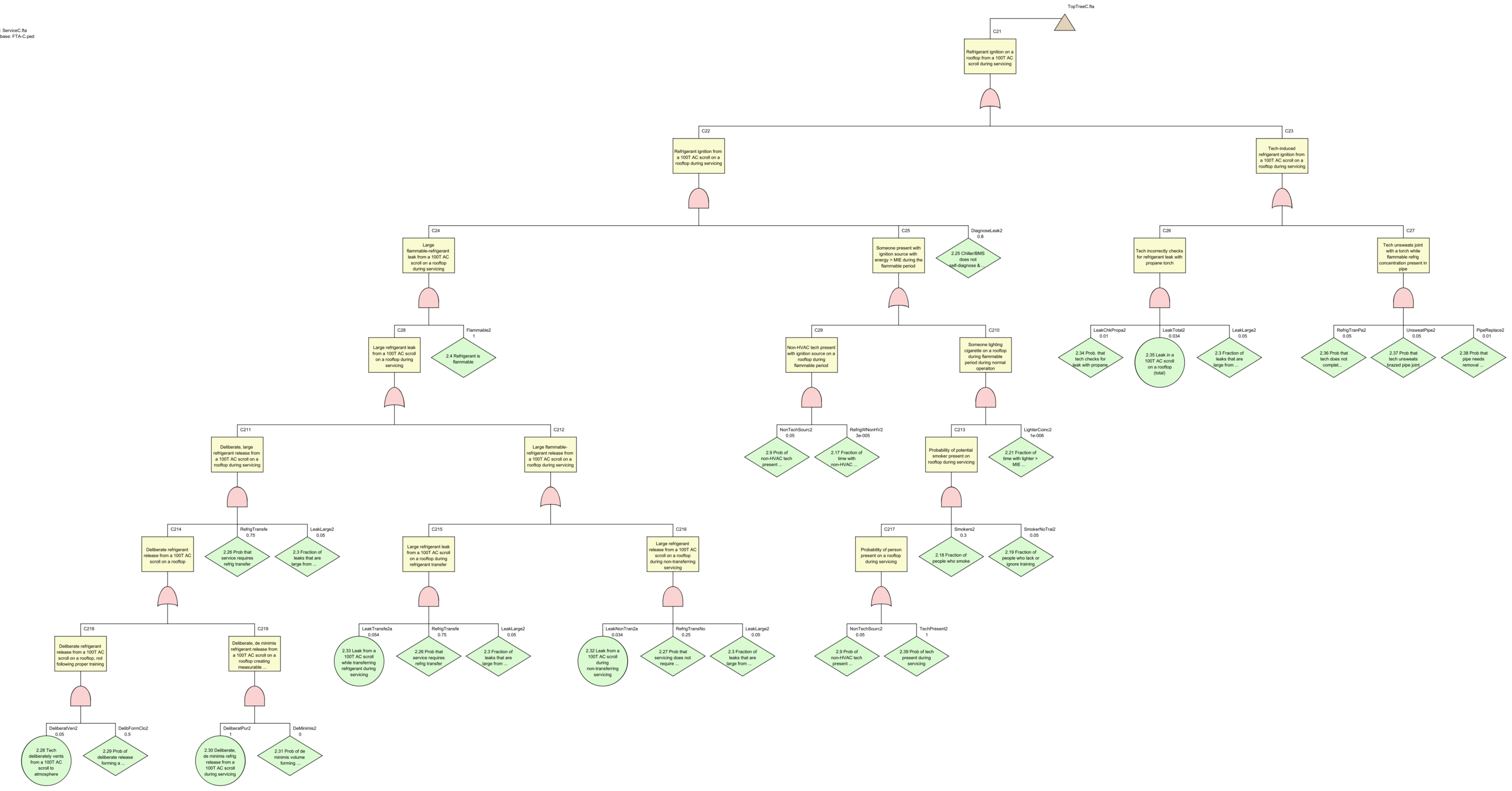


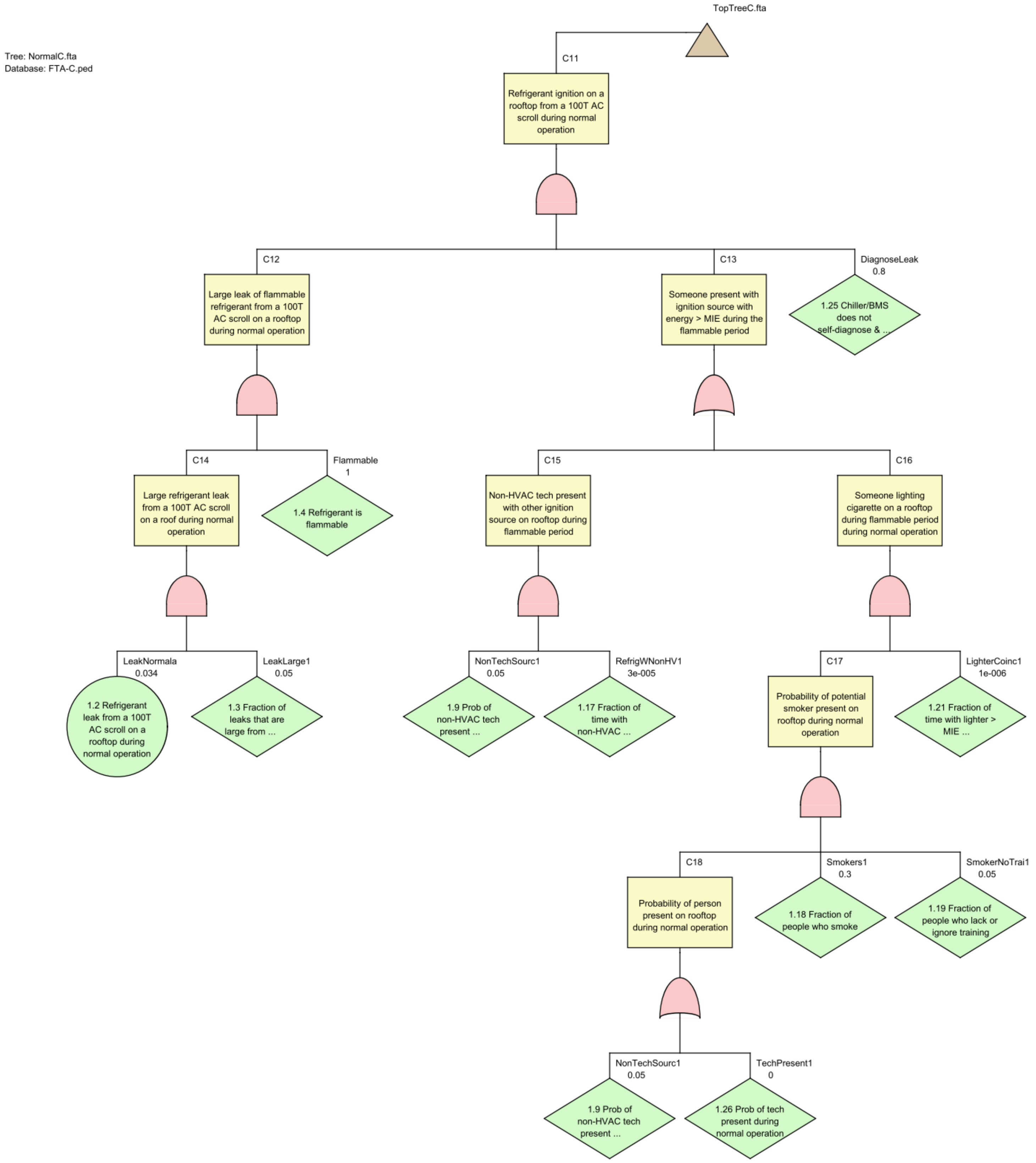
Tree: InstallC.fta
Database: FTA-C.ped



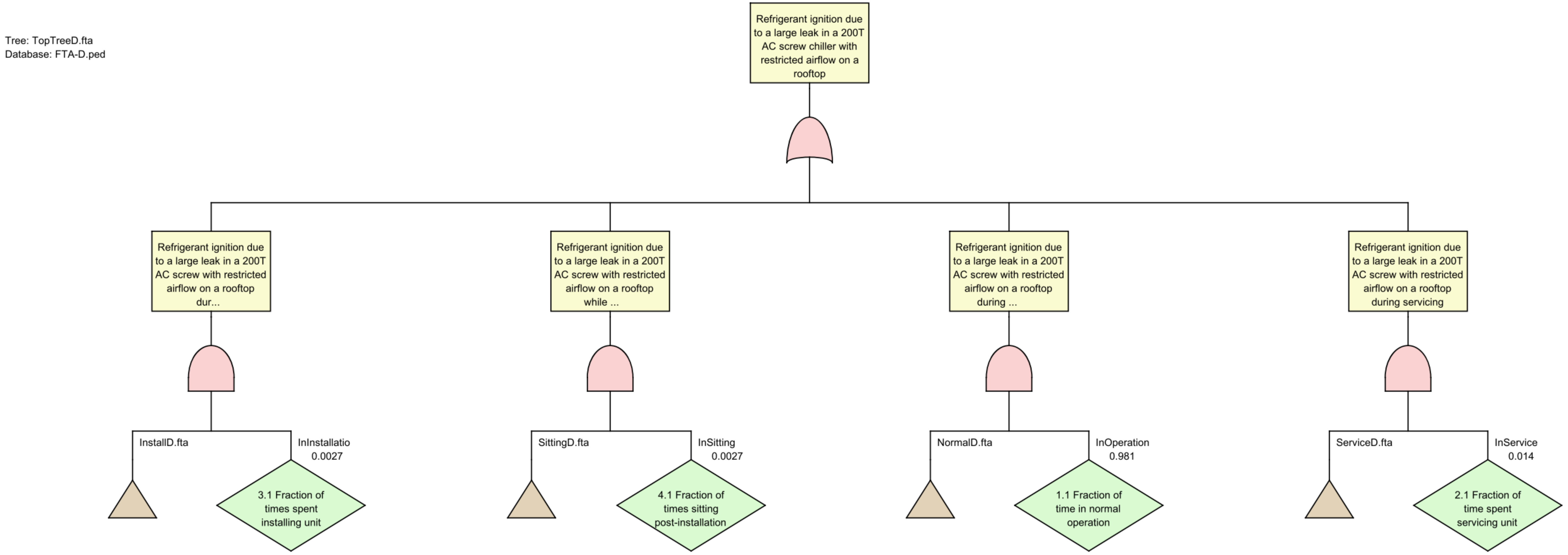

Tree: SittingC.fta
Database: FTA-C.ped
TopTreeC.fta
C41
Refrigerant ignition on a rooftop with a 100T AC scroll while sitting post-installation
C42
Large flammable-refrigerant leak from a 100T AC scroll on a rooftop while sitting post-installation
C43
Someone present with ignition source with energy > MIE during the flammable period
DiagnoseLeak4
0.9
4.25 Chiller/BMS does not self-diagnose & ...
C44
Large refrigerant leak from a 100T AC scroll on a rooftop while sitting post-installation
Flammable4
1
4.4 Refrigerant is flammable
C45
Someone present with ignition source on a rooftop during flammable period during installation
C46
Someone lighting cigarette on a rooftop during flammable period while sitting post-installation
C47
Large refrigerant leak from a 100T AC scroll on a rooftop while sitting post-installation (non-accident)
C48
Large refrigerant leak from a 100T scroll on a rooftop while sitting post-installation due to an accident
NonTechSourc4
0.9
4.9 Prob of non-HVAC tech present ...
RefrigWNonHV4
3e-005
4.17 Fraction of time with non-HVAC ...
C49
Probability of potential smoker present on rooftop while sitting post-installation
LighterCoinc4
1e-006
4.21 Fraction of time with lighter > MIE ...
LeakOff4
0.001
4.42 Probability of a leak while chiller is off while sitting post-installation
LeakLarge4
0.001
4.3 Fraction of leaks that are large while ...
AccidentLeak4
0.01
4.41 Probability of a leak due to an accident
LeakLargeOff4
0.01
4.40 Fraction of accident leaks that are large
C410
Probability of person present on rooftop while sitting post-installation
Smokers4
0.3
4.18 Fraction of people who smoke
SmokerNoTrai4
0.05
4.19 Fraction of people who lack or ignore training
NonTechSourc4
0.9
4.9 Prob of non-HVAC tech present ...
TechPresent4
0
4.39 Prob of tech present while sitting ...

Tree: ServiceC.fta
Database: FTA-C.ped

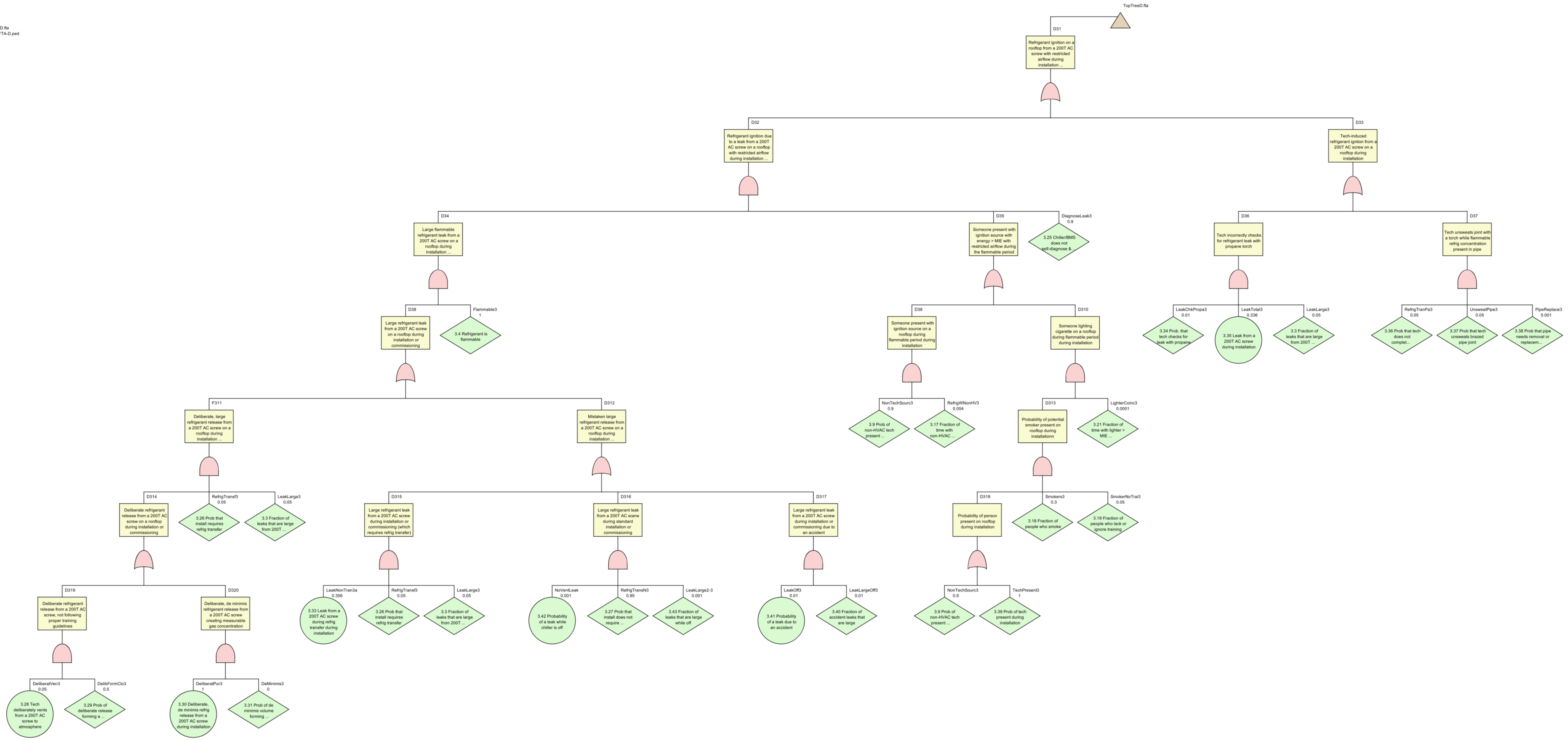



Tree: NormalC.fta
Database: FTA-C.ped
TopTreeC.fta
C11
Refrigerant ignition on a rooftop from a 100T AC scroll during normal operation
C12
Large leak of flammable refrigerant from a 100T AC scroll on a rooftop during normal operation
C13
Someone present with ignition source with energy > MIE during the flammable period
DiagnoseLeak
0.8
1.25 Chiller/BMS does not self-diagnose & ...
C14
Large refrigerant leak from a 100T AC scroll on a roof during normal operation
Flammable
1
1.4 Refrigerant is flammable
C15
Non-HVAC tech present with other ignition source on rooftop during flammable period
C16
Someone lighting cigarette on a rooftop during flammable period during normal operation
LeakNormala
0.034
1.2 Refrigerant leak from a 100T AC scroll on a rooftop during normal operation
LeakLarge1
0.05
1.3 Fraction of leaks that are large from ...
NonTechSourc1
0.05
1.9 Prob of non-HVAC tech present ...
RefrigWNonHV1
3e-005
1.17 Fraction of time with non-HVAC ...
C17
Probability of potential smoker present on rooftop during normal operation
LighterCoinc1
1e-006
1.21 Fraction of time with lighter > MIE ...
C18
Probability of person present on rooftop during normal operation
Smokers1
0.3
1.18 Fraction of people who smoke
SmokerNoTrai1
0.05
1.19 Fraction of people who lack or ignore training
NonTechSourc1
0.05
1.9 Prob of non-HVAC tech present ...
TechPresent1
0
1.26 Prob of tech present during normal operation

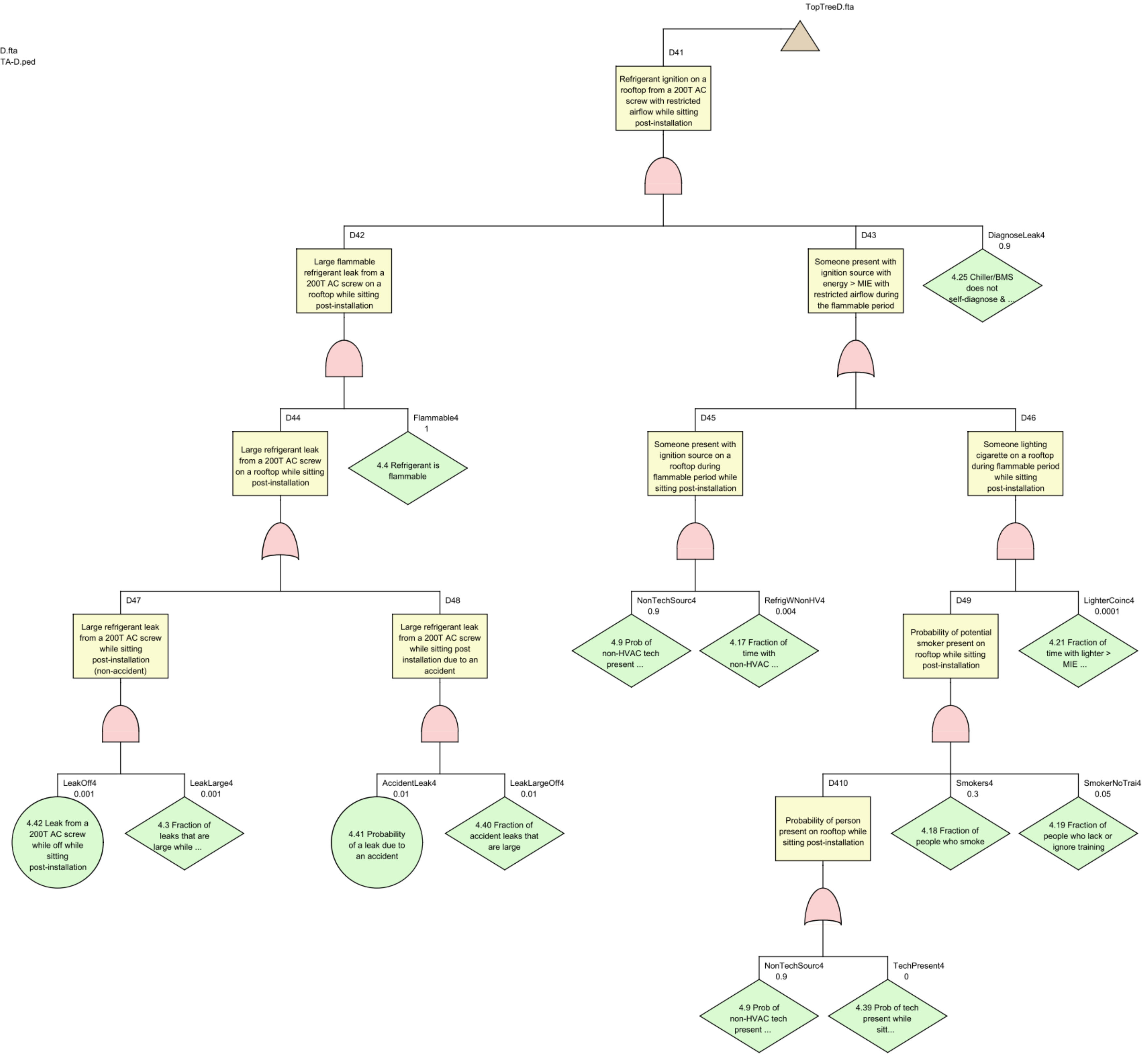
Appendix D. Fault Trees – Scenario D



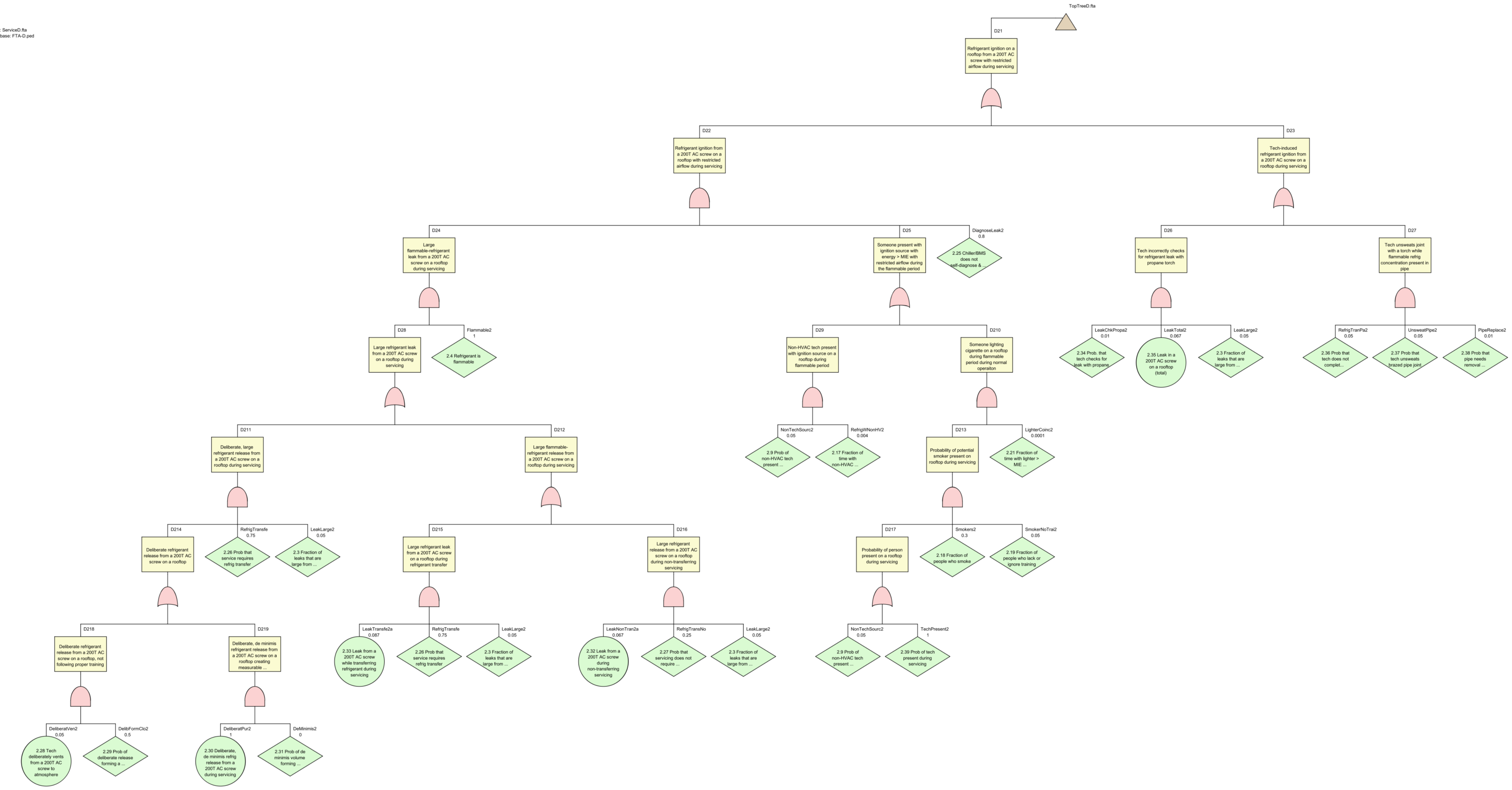
Tree: InstallD.fta
Database: FTA-D.ped



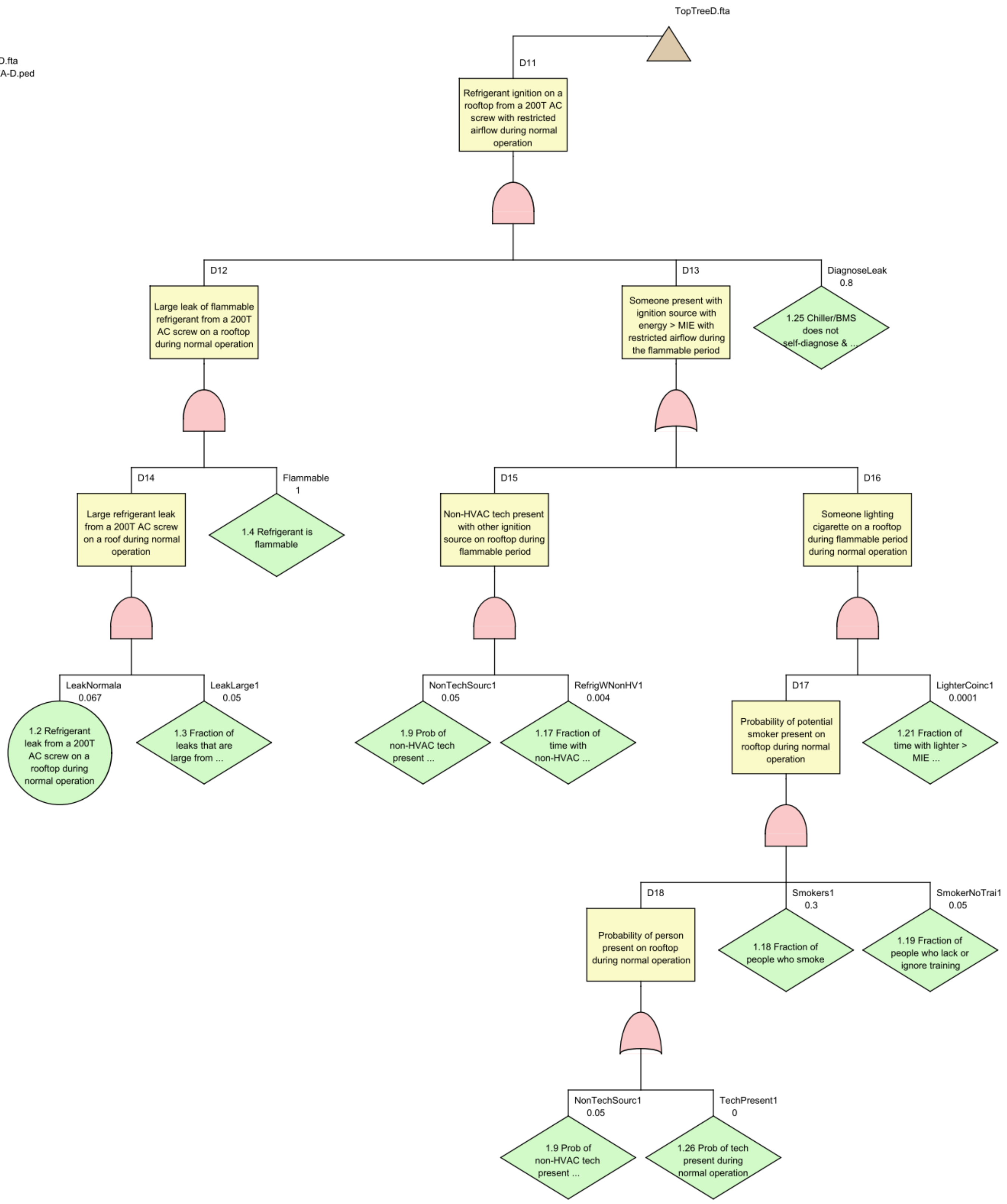
Tree: SittingD.fta
Database: FTA-D.ped



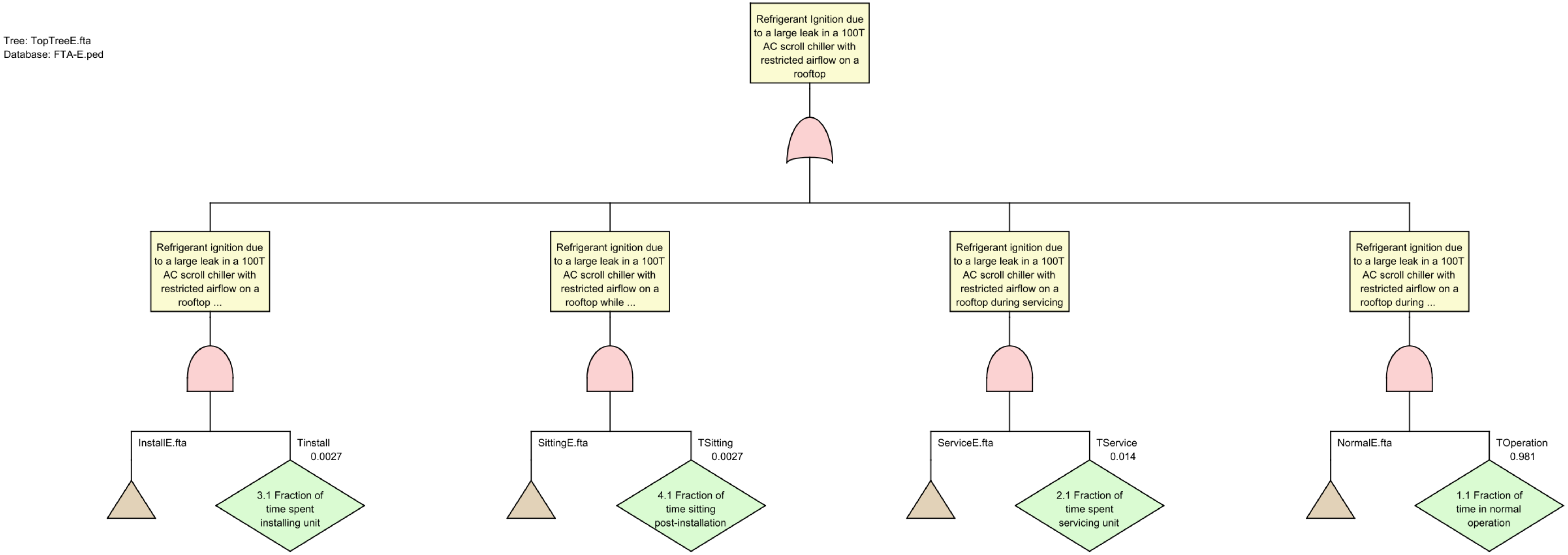
Tree: ServiceD.fta
Database: FTA-D.ped



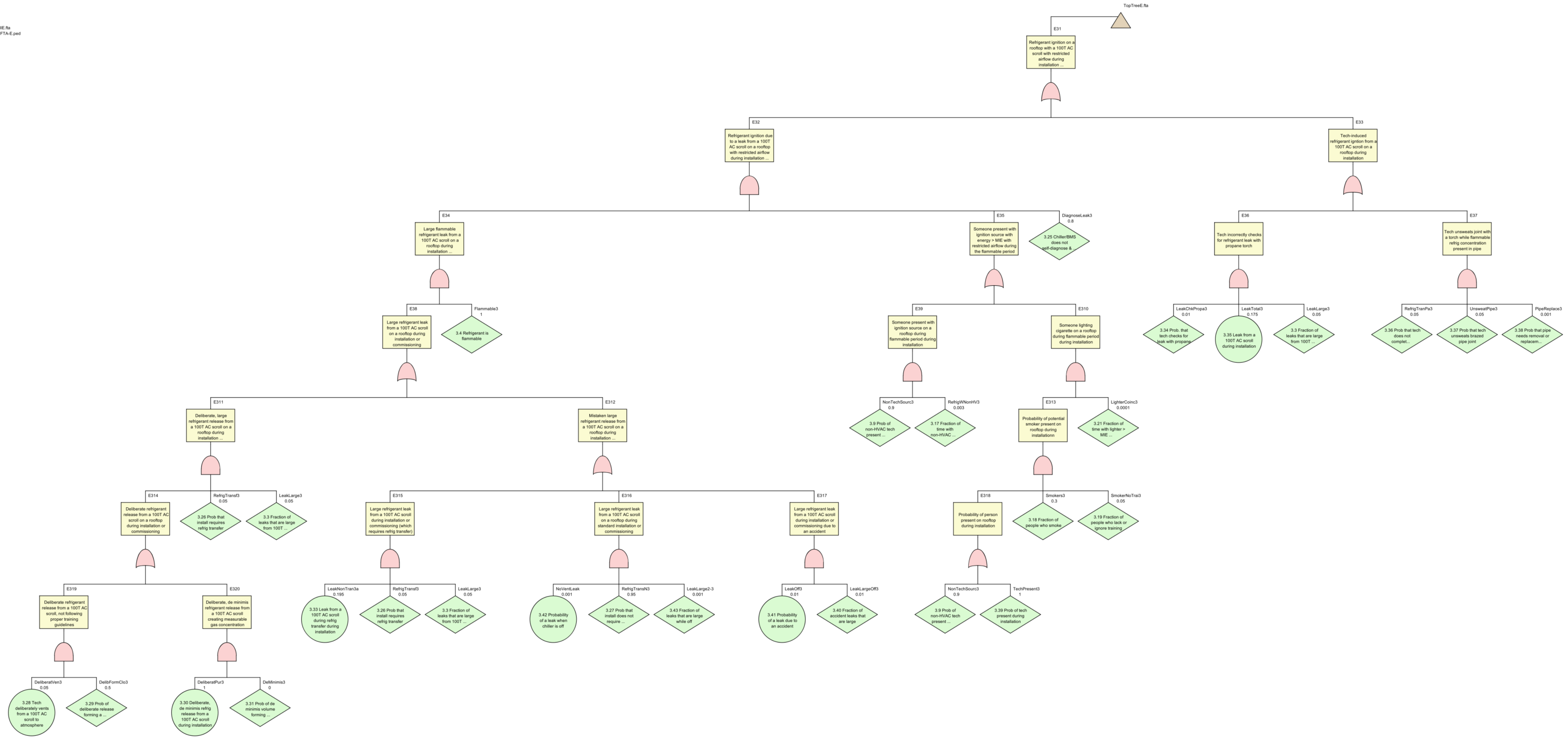
Tree: NormalD.fta
Database: FTA-D.ped



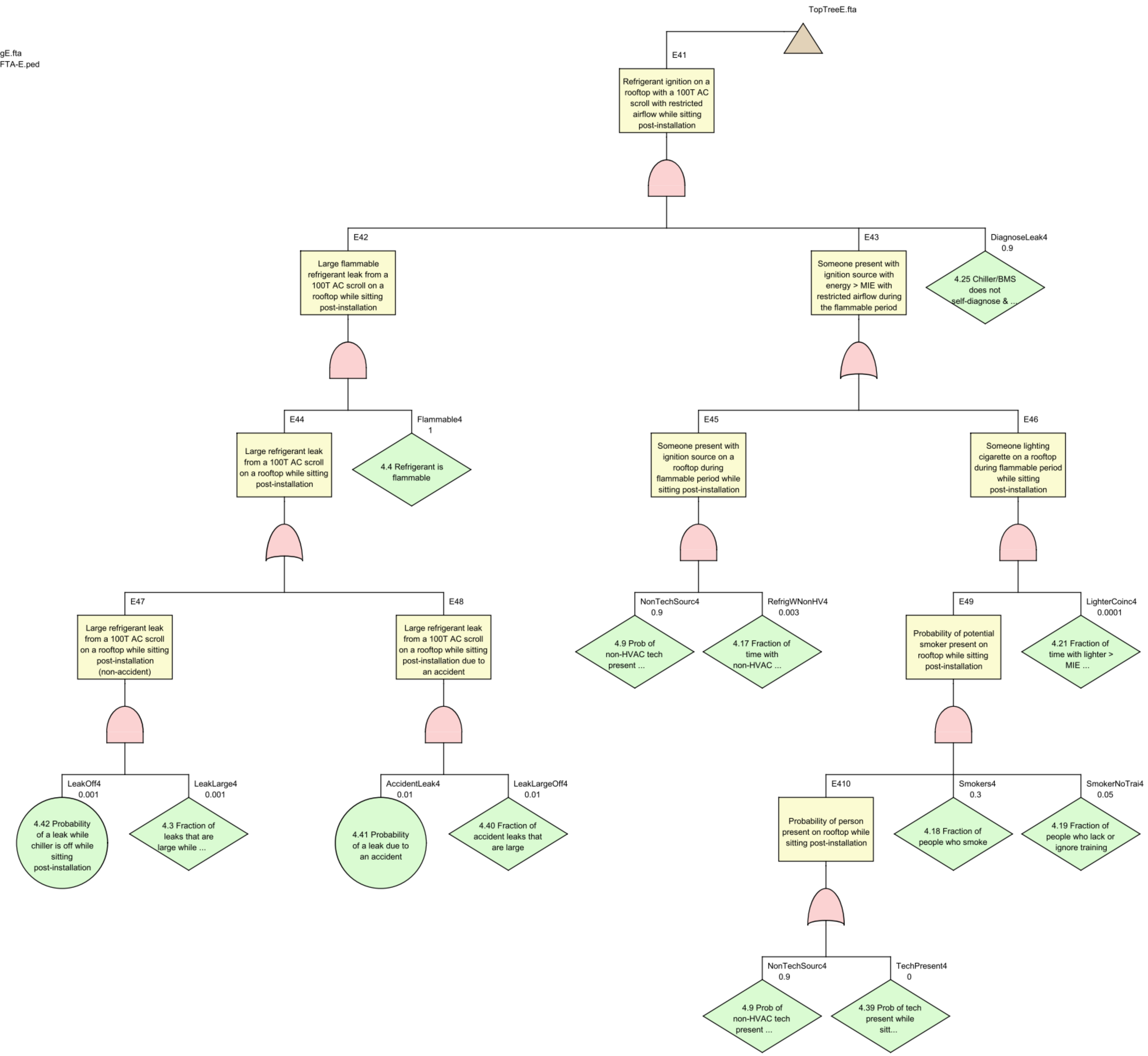
Appendix E. Fault Trees – Scenario E

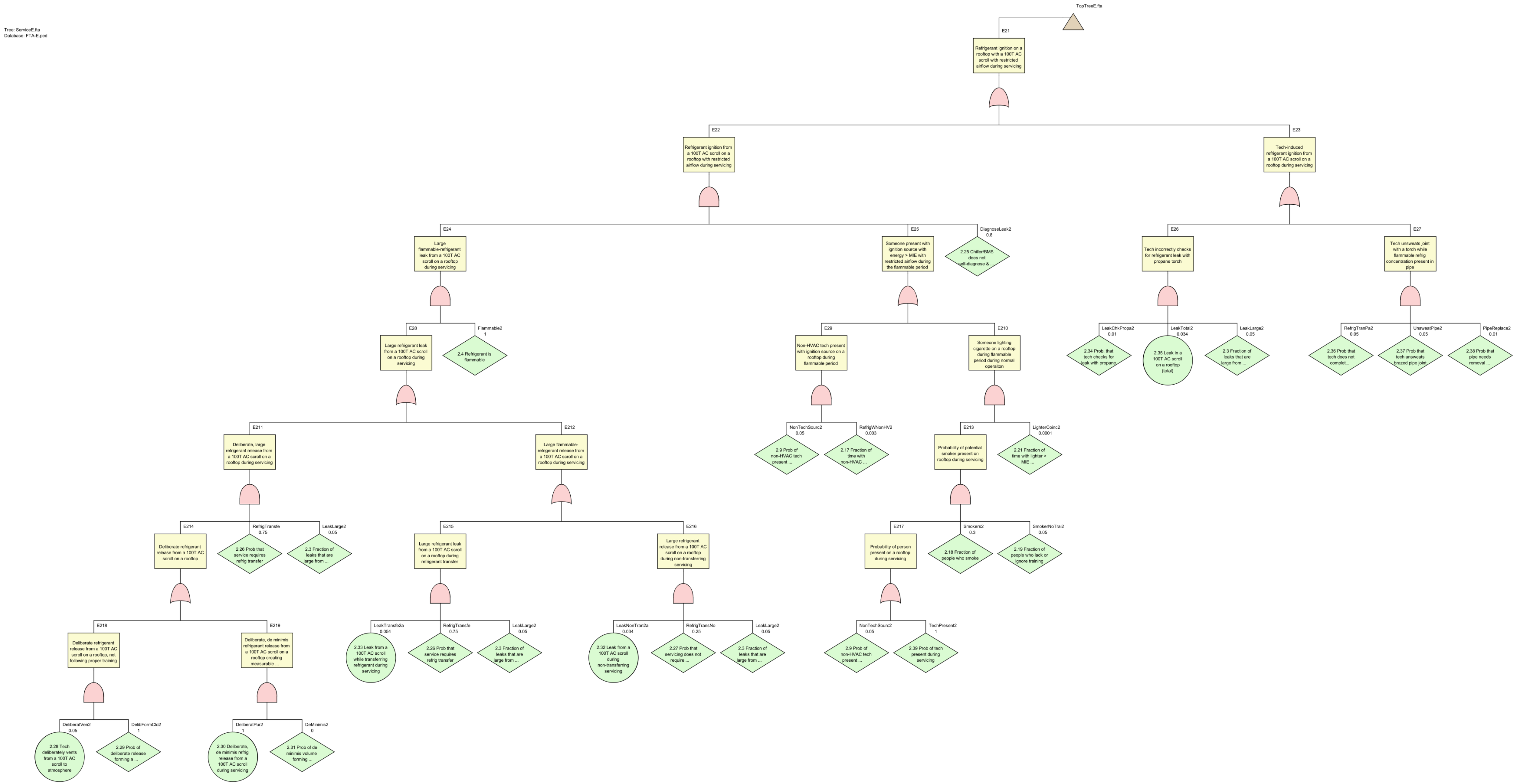


Tree: InstallE.fta
Database: FTA-E.ped

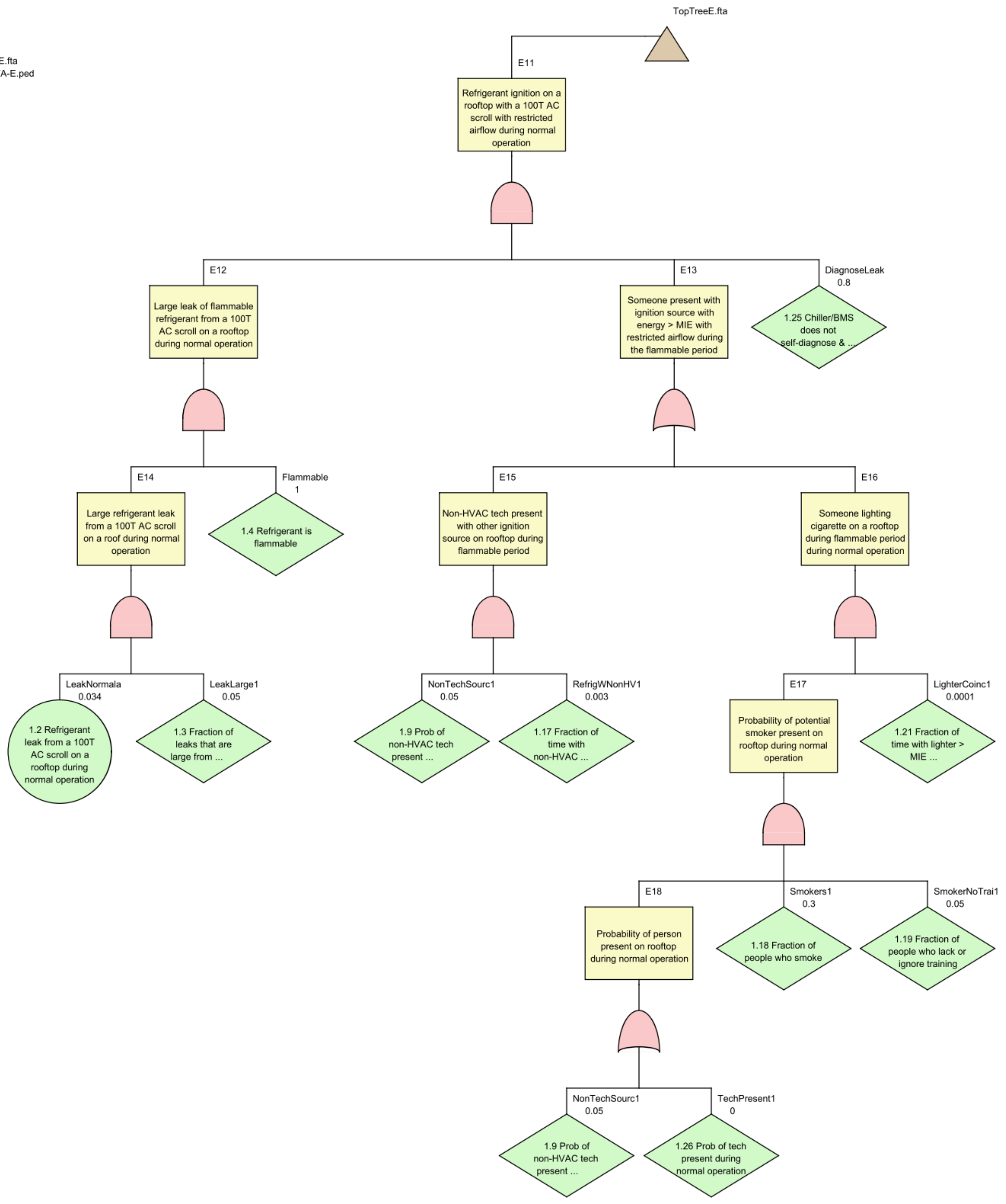


Tree: SittingE.fta
Database: FTA-E.ped




Tree: ServiceE.fta
Database: FTA-E.ped
TopTreeE.fta
E21
Refrigerant ignition on a rooftop with a 100T AC scroll with restricted airflow during servicing
E22
Refrigerant ignition from a 100T AC scroll on a rooftop with restricted airflow during servicing
E23
Tech-induced refrigerant ignition from a 100T AC scroll on a rooftop during servicing
E24
Large flammable-refrigerant leak from a 100T AC scroll on a rooftop during servicing
E25
Someone present with ignition source with energy > MIE with restricted airflow during the flammable period
DiagnoseLeak2
0.8
2.25 Chiller/BMS does not self-diagnose & ...
E26
Tech incorrectly checks for refrigerant leak with propane torch
E27
Tech unsweats joint with a torch while flammable refrig concentration present in pipe
E28
Large refrigerant leak from a 100T AC scroll on a rooftop during servicing
Flammable2
1
2.4 Refrigerant is flammable
E29
Non-HVAC tech present with ignition source on a rooftop during flammable period
E210
Someone lighting cigarette on a rooftop during flammable period during normal operaiton
LeakChkPropa2
0.01
2.34 Prob. that tech checks for leak with propane
LeakTotal2
0.034
2.35 Leak in a 100T AC scroll on a rooftop (total)
LeakLarge2
0.05
2.3 Fraction of leaks that are large from ...
RefrigTranPa2
0.05
2.36 Prob that tech does not complet...
UnsweatPipe2
0.05
2.37 Prob that tech unsweats brazed pipe joint
PipeReplace2
0.01
2.38 Prob that pipe needs removal ...
E211
Deliberate, large refrigerant release from a 100T AC scroll on a rooftop during servicing
E212
Large flammable-refrigerant release from a 100T AC scroll on a rooftop during servicing
NonTechSourc2
0.05
2.9 Prob of non-HVAC tech present ...
RefrigWNonHV2
0.003
2.17 Fraction of time with non-HVAC ...
E213
Probability of potential smoker present on rooftop during servicing
LighterCoinc2
0.0001
2.21 Fraction of time with lighter > MIE ...
E214
Deliberate refrigerant release from a 100T AC scroll on a rooftop
RefrigTransfe
0.75
2.26 Prob that service requires refrig transfer
LeakLarge2
0.05
2.3 Fraction of leaks that are large from ...
E215
Large refrigerant leak from a 100T AC scroll on a rooftop during refrigerant transfer
E216
Large refrigerant release from a 100T AC scroll on a rooftop during non-transferring servicing
E217
Probability of person present on a rooftop during servicing
Smokers2
0.3
2.18 Fraction of people who smoke
SmokerNoTrai2
0.05
2.19 Fraction of people who lack or ignore training
E218
Deliberate refrigerant release from a 100T AC scroll on a rooftop, not following proper training
E219
Deliberate, de minimis refrigerant release from a 100T AC scroll on a rooftop creating measurable ...
LeakTransfe2a
0.054
2.33 Leak from a 100T AC scroll while transferring refrigerant during servicing
RefrigTransfe
0.75
2.26 Prob that service requires refrig transfer
LeakLarge2
0.05
2.3 Fraction of leaks that are large from ...
LeakNonTran2a
0.034
2.32 Leak from a 100T AC scroll during non-transferring servicing
RefrigTransNo
0.25
2.27 Prob that servicing does not require ...
LeakLarge2
0.05
2.3 Fraction of leaks that are large from ...
NonTechSourc2
0.05
2.9 Prob of non-HVAC tech present ...
TechPresent2
1
2.39 Prob of tech present during servicing
DeliberatVen2
0.05
2.28 Tech deliberately vents from a 100T AC scroll to atmosphere
DelibFormClo2
1
2.29 Prob of deliberate release forming a ...
DeliberatPur2
1
2.30 Deliberate, de minimis refrig release from a 100T AC scroll during servicing
DeMinimis2
0
2.31 Prob of de minimis volume forming ...

Tree: NormalE.fta
Database: FTA-E.ped



Appendix F. Fault Trees – FTA Justification

F.1 *Fault Tree Rationale Scenario A - 400T Water-cooled screw in a mechanical room*

Fault Tree Rationale - 400T Water-cooled screw in a mechanical room				
ID		**Event (*indicates that value is repeated from prior FTA branch)**	**Probability**	**Source/Discussion**
Normal Operation with Ventilation				
1.1		Fraction of time in normal operation	0.559	Assumes that system is running for approximately 358 days per year with 57% ventilation runtime - based on NCI analysis of CBECS 2003 buildings with chillers - assume 100% runtime during occupied hours and runtime by CZ for off hours: 10% CZ1, 30% CZ2, 50% CZ3, 70% CZ4, 90% CZ5
1.2a		Refrigerant leak from a 400T WC screw in a mech room during normal operation (UnitA)	0.055	From Mfr collected warranty data - Assumes 1 possible leak per unit, based on number of leaks per year expected from total population of such units. Assume even distribution of leaks (annualized)
1.2b		Refrigerant leak from a 400T WC screw in a mech room during normal operation (UnitB)	0.055	From Mfr collected warranty data - Assumes 1 possible leak per unit, based on number of leaks per year expected from total population of such units. Assume even distribution of leaks
1.3		Fraction of leaks that are large from 400T WC screws during normal operation	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
1.4		Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
1.5		Prob. of spark source present in a mech room during normal operation	1	Potential sources present in all mechanical rooms.
1.6		Prob. of hot surface source present in a mech room during normal operation	0.5	Estimate based on potential presence of generator or other such hot surface source - Independent of refrigerant presence and operating state.
1.7		Prob of boiler present in a mech room	0.2	Based on discussion with technician and strict code (E.g., ASHRAE 15) associated with locating combustion equipment and refrigerant equipment in the same mechanical room. This is likely more common in basements with smaller systems. ASHRAE 15 does not allow combustion equipment in chiller room unless combustion air is ducted in from outside air. Risk arises if ducting contains a leak and refrigerant vapor enters the combustion air ducting.
1.8		Prob of boiler setup not to code, exposing flame	0.01	ASHRAE 15 mandates that boiler may not be present unless combustion air is ducted in from outside the mech room. Accordingly, only a boiler that is not setup to code may have exposed flame.
1.9		Prob of non-HVAC tech present in mech room during normal operation	0.05	Estimated - Independent of normal operation, servicing, installation
1.14		Fraction of time with spark > MIE and flammable concentration	0.015	Based on NCI Analysis
1.15		Fraction of time with hot surface > MIE and flammable concentration	0.0016	Based on NCI Analysis
1.16		Fraction of time with flame > MIE and flammable concentration	0.24	Based on NCI Analysis
1.17		Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.0027	Based on NCI Analysis
1.18		Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
1.19		Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 due to additional deterants likely in modern workplace (e.g., signs)
1.21		Fraction of time with lighter flame > MIE and flammable concentration	0.0002	Based on NCI Analysis
1.23		Prob of exhaust ventilation malfunction during normal operation	0.00027	DOE motor TSD (Technical Support Document http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/em_preanalysis_tsdch08.pdf) indicates 10.1-12.5 year average life for 3 example NEMA Design B motors (DOE equipment Class Group 1, typical of HVAC fan motors from 1 to 500 HP). We round up to 10% failure to acount for other less likely failures such as damper motors, damper linkages, etc. Assuming 1 day of down time, we calculate 1/365*10%. May include failure of either standard speed ventilation or exhaust-speed ventilation. Assumes functioning standard (non-exhaust) ventilation - in case of complete ventilation failure, analysis assumes that personnel are notified and precautions taken because it is likely combined with failure of other major building systems.
1.24		Monitor is broken or malfunctioning	0.05	Estimated based on discussion with technicians - may be due to lack of calibration, disabling by personnel, or malfunction. Expected lifetime is 5-7 years.
1.25		Chiller/BMS does not self-diagnose and notify	0.8	Estimate - includes ability of communications system to transmit failure code to BMS
1.26		Prob that technician present during normal operation	0	By definition, technician not present during normal operation
Servicing				
2.1		Fraction of time spent servicing unit	0.014	Assume 5 days/yr, accounts for larger downtime some yrs for substantial teardowns, but minimal servicing some years.
2.3	*	Fraction of leaks that are large from 400T WC chiller during servicing	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
2.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
2.5	*	Prob. of spark source present in a mech room during servicing	1	Potential sources present in all mechanical rooms.
2.6	*	Prob. of hot surface source present in a mech room during servicing	0.5	Estimate based on potential presence of generator or other such hot surface source - Independent of refrigerant presence and operating state.
2.7	*	Prob of boiler present in a mech room	0.2	Based on discussion with technician and strict code (E.g., ASHRAE 15) associated with locating combustion equipment and refrigerant equipment in the same mechanical room. This is likely more common in basements with smaller systems. ASHRAE 15 does not allow combustion equipment in chiller room unless combustion air is ducted in from outside air. Risk arises if ducting contains a leak and refrigerant vapor enters the combustion air ducting.
2.8	*	Prob of boiler setup not to code, exposing flame	0.01	ASHRAE 15 mandates that boiler may not be present unless combustion air is ducted in from outside the mech room. Accordingly, only a boiler that is not setup to code may have exposed flame.
2.9	*	Prob of non-HVAC tech present in mech room during servicing	0.05	Estimated - Independent of normal operation, servicing, installation
2.14	*	Fraction of time with spark > MIE and flammable refrig concentration	0.015	Based on NCI Analysis
2.15	*	Fraction of time with hot surface > MIE and flammable refrig concentration	0.0016	Based on NCI Analysis
2.16	*	Fraction of time with flame > MIE and flammable concentration	0.24	Based on NCI Analysis
2.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.0027	Based on NCI Analysis
2.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
2.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 due to additional deterants likely in modern workplace (e.g., signs)
2.21	*	Fraction of time with lighter flame > MIE and flammable concentration	0.0002	Based on NCI Analysis
2.23	*	Prob of exhaust ventilation malfunction during servicing	0.00027	DOE motor TSD (Technical Support Document http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/em_preanalysis_tsdch08.pdf) indicates 10.1-12.5 year average life for 3 example NEMA Design B motors (DOE equipment Class Group 1, typical of HVAC fan motors from 1 to 500 HP). We round up to 10% failure to acount for other less likely failures such as damper motors, damper linkages, etc. Assuming 1 day of down time, we calculate 1/365*10%. May include failure of either standard speed ventilation or exhaust-speed ventilation. Assumes functioning standard (non-exhaust) ventilation - in case of complete ventilation failure, analysis assumes that personnel are notified and precautions taken because it is likely combined with failure of other major building systems.
2.24	*	Monitor is broken or malfunctioning	0.05	Estimated based on discussion with technicians - may be due to lack of calibration, disabling by personnel, or malfunction. Expected lifetime is 5-7 years.
2.25	*	Chiller/BMS does not self-diagnose and notify	0.8	Estimate - includes ability of communications system to transmit failure code to BMS

Fault Tree Rationale - 400T Water-cooled screw in a mechanical room

ID	Event (*indicates that value is repeated from prior FTA branch)		Probability	Source/Discussion
2.26		Prob that service requires refrig transfer	0.75	Estimated based on discussions with technicians. Higher than 0.2 value from Goetzler, 1998, "Risk Assessment…" due to differences in commercial and residential systems.
2.27		Prob that service does not require refrig transfer	0.25	Time that is not associated with 2.26
2.28		Tech deliberately vents from a 400T WC screw to atmosphere	0.05	Goetzler, 1998, "Risk Assessment…"
2.29		Prob of deliberate release forming a flammable concentration	0.5	Estimated that half of deliberate releases are high volume releases
2.30		Deliberate, de minimis refrig release from a 400T WC screw during servicing	1	Assumption based on fact that technicians vent de minimis amounts during every refrigerant transfer
2.31		Prob of de minimis volume forming a flammable concentration	0	Engineering assumption based on properties of 2L refrigerants
2.32a		Leak from 1 of 2 400T WC screws in a mech room during non-transferring servicing (UnitA)	0.055	Assume same as Normal Operation leaks
2.32b		Leak from 1 of 2 400T WC screws in a mech room during non-transferring servicing (UnitB)	0.055	Assume same as Normal Operation leaks
2.33a		Leak in a mech room while transferring refrigerant during servicing (UnitA)	0.075	Assumed to be 2% greater likelihood than during non-transferring installation - based on Goetzler 1998
2.33b		Leak in a mech room while transferring refrigerant during servicing (UnitB)	0.075	Assumed to be 2% greater likelihood than during non-transferring installation - based on Goetzler 1998
2.34		Prob that technicians checks for leaks with propane	0.01	Goetzler, 1998, "Risk Assessment…" - Reduced to 1% due to increased awareness and training since study
2.35a		Likelihood of a leak in a 400T WC screw in a mech room (total - Unit A)	0.055	Based on data collected from manufacturers on 400T WC Screw chillers
2.35b		Likelihood of a leak in a 400T WC screw in a mech room (total - Unit B)	0.055	Based on data collected from manufacturers on 400T WC Screw chillers
2.36		Prob that tech does not completely evacuate refrigerant before removing pipe	0.05	Goetzler, 1998, "Risk Assessment…" - Equivalent to value for 'Tech lacks training or proper equipment"
2.37		Prob that tech unsweats brazed pipe joint	0.05	Goetzler, 1998, "Risk Assessment…" - Equivalent to value for 'Tech lacks training or proper equipment"
2.38		Prob that pipe needs removal or replacement during servicing	0.01	Estimated
2.39		Prob that technician present during servicing	1	By definition, technician present during servicing
Installation/Commissioning				
3.1		Fraction of time spent installing unit or conducting major renovations	0.0027	Includes commissioning, etc. Estimate - assume approximately 25 days per 25 years, or 1/365 per year
3.3	*	Fraction of leaks from 400T WC screws during installation that are large	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
3.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
3.5	*	Prob. of spark source present in a mech room during installation	1	Potential sources present in all mechanical rooms.
3.6	*	Prob. of hot surface source present in a mech room during installation	0.5	Estimate based on potential presence of generator or other such hot surface source - Independent of refrigerant presence and operating state.
3.7	*	Prob of boiler present in a mech room	0.2	Based on discussion with technician and strict code (E.g., ASHRAE 15) associated with locating combustion equipment and refrigerant equipment in the same mechanical room. This is likely more common in basements with smaller systems. ASHRAE 15 does not allow combustion equipment in chiller room unless combustion air is ducted in from outside air. Risk arises if ducting contains a leak and refrigerant vapor enters the combustion air ducting.
3.8	*	Prob of boiler setup not to code, exposing flame	0.01	ASHRAE 15 mandates that boiler may not be present unless combustion air is ducted in from outside the mech room. Accordingly, only a boiler that is not setup to code may have exposed flame.
3.9		Prob of non-HVAC tech present in mech room during installation	0.9	Estimate - substantially higher than servicing or normal operation
3.14		Fraction of time with spark > MIE and flammable concentration	0.016	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
3.15		Fraction of time with hot surface > MIE and flammable concentration	0.005	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
3.16		Fraction of time with flame > MIE and flammable concentration	0.29	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
3.17		Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.006	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
3.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
3.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 due to additional deterants likely in modern workplace (e.g., signs)
3.21		Fraction of time with lighter flame > MIE and flammable concentration	0.0004	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
3.23	*	Prob of exhaust ventilation malfunction during installation	0.00027	DOE motor TSD (Technical Support Document http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/em_preanalysis_tsdch08.pdf) indicates 10.1-12.5 year average life for 3 example NEMA Design B motors (DOE equipment Class Group 1, typical of HVAC fan motors from 1 to 500 HP). We round up to 10% failure to acount for other less likely failures such as damper motors, damper linkages, etc. Assuming 1 day of down time, we calculate 1/365*10%. May include failure of either standard speed ventilation or exhaust-speed ventilation. Assumes functioning standard (non-exhaust) ventilation - in case of complete ventilation failure, analysis assumes that personnel are notified and precautions taken because it is likely combined with failure of other major building systems.
3.24		Monitor is broken or malfunctioning	0.75	Estimated based on discussion with technicians - may be due to lack of calibration, disabling by personnel, or malfunction. Expected lifetime is 5-7 years.
3.25		Chiller/BMS does not self-diagnose and notify	0.9	Estimated to be greater than during all normal operations because commissioning is not yet complete
3.26		Prob that installation requires refrig transfer	0.05	Estimated based on discussions with technicians - vast majority are shipped with complete charge
3.27		Prob that installation does not require refrig transfer	0.95	Time that is not associated with 3.26
3.28	*	Tech deliberately vents to atmosphere	0.05	Goetzler, 1998, "Risk Assessment…"
3.29	*	Prob of deliberate release forming a flammable concentration	0.5	Estimated that half of deliberate releases are high volume releases
3.30	*	Deliberate, de minimis refrig release from a 400T WC screw during installation	1	Assumption based on fact that technicians vent de minimis amounts during every refrigerant transfer
3.31	*	Prob of de minimis volume forming a flammable concentration	0	Engineering assumption based on properties of 2L refrigerants
3.33a		Leak in a mech room during refrig transfer during installation (UnitA)	0.254	Assumed to be 2% greater likelihood than during non-transferring installation - based on Goetzler 1998
3.33b		Leak in a mech room during refrig transfer during installation (UnitB)	0.254	Assumed to be 2% greater likelihood than during non-transferring installation - based on Goetzler 1998
3.34	*	Prob that technicians checks for leaks with propane	0.01	Goetzler, 1998, "Risk Assessment…" - Reduced to 1% due to increased awareness and training since study
3.35a		Leak from a 400T WC screw during installation (Unit A)	0.234	From Mfr collected warranty data (annualized)
3.35b		Leak from a 400T WC screw during installation (Unit B)	0.234	From Mfr collected warranty data (annualized)
3.36	*	Prob that tech does not completely evacuate refrigerant before removing pipe	0.05	Goetzler, 1998, "Risk Assessment…" - Equivalent to value for 'Tech lacks training or proper equipment"
3.37	*	Prob that tech unsweats brazed pipe joint	0.05	Goetzler, 1998, "Risk Assessment…" - Equivalent to value for 'Tech lacks training or proper equipment"
3.38		Prob that pipe needs removal or replacement during installation	0.001	Estimate
3.39		Prob that technician present during installation	1	By definition, technician present during installation
3.40		Fraction of accident leaks that are large	0.01	Calculated based on assumption that\ total probability of large leak due to an accident is approximately equal to rate of fatal injury in building construction industry: http://www.bls.gov/iif/oshwc/cfoi/worker_memorial.htm
3.41a		Probability of a leak due to an accident (Unit A)	0.01	Estimated to be less than the nonfatal occupational injury rate of 3% - http://www.bls.gov/iif/oshwc/osh/os/ostb3193.pdf

Fault Tree Rationale - 400T Water-cooled screw in a mechanical room

ID	Event (*indicates that value is repeated from prior FTA branch)	Probability	Source/Discussion
3.41b	Probability of a leak due to an accident (Unit B)	0.01	Estimated to be less than the nonfatal occupational injury rate of 3% - http://www.bls.gov/iif/oshwc/osh/os/ostb3193.pdf
3.42a	Probability of a leak while chiller is off (Unit A)	0.001	Estimated from NCI analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
3.42b	Probability of a leak while chiller is off (Unit B)	0.001	Estimated from NCI analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
3.43	Fraction of leaks that are large while off	0.001	Estimated from NCI analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
Sitting Post-Installation			
4.1	Fraction of time spent sitting post-installation	0.0270	Based on discussion with technicians and building managers, this is highly variable depending on the installation, and may be zero for some retrofit cases. Absent more concrete data, assumed to be equivalent to installation.
4.3	Fraction of leaks that are large while sitting post-installation	0.001	Estimated from NCI analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
4.4	* Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
4.5	* Prob. of spark source present in a mech room while sitting post-installation	1	Potential sources present in all mechanical rooms.
4.6	* Prob. of hot surface source present in a mech room while sitting post-installation	0.5	Estimate based on potential presence of generator or other such hot surface source - Independent of refrigerant presence and operating state.
4.7	* Prob of boiler present in a mech room	0.2	Based on discussion with technician and strict code (E.g., ASHRAE 15) associated with locating combustion equipment and refrigerant equipment in the same mechanical room. This is likely more common in basements with smaller systems. ASHRAE 15 does not allow combustion equipment in chiller room unless combustion air is ducted in from outside air. Risk arises if ducting contains a leak and refrigerant vapor enters the combustion air ducting.
4.8	* Prob of boiler setup not to code, exposing flame	0.01	ASHRAE 15 mandates that boiler may not be present unless combustion air is ducted in from outside the mech room. Accordingly, only a boiler that is not setup to code may have exposed flame.
4.9	* Prob of non-HVAC tech present in mech room while sitting post-installation	0.9	Estimate - substantially higher than servicing or normal operation
4.14	* Fraction of time with spark > MIE and flammable concentration	0.016	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
4.15	* Fraction of time with hot surface > MIE and flammable concentration	0.005	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
4.16	* Fraction of time with flame > MIE and flammable concentration	0.29	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
4.17	* Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.006	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
4.18	* Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
4.19	* Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 due to additional deterants likely in modern workplace (e.g., signs)
4.21	* Fraction of time with lighter flame > MIE and flammable concentration	0.0004	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
4.24	* Monitor is broken or malfunctioning	0.75	Estimated based on discussion with technicians - may be due to lack of calibration, disabling by personnel, or malfunction. Expected lifetime is 5-7 years.
4.25	* Chiller/BMS does not self-diagnose and notify	0.9	Estimated to be greater than during all normal operations because commissioning is not yet complete
4.39	Prob that technician present during while sitting post-installation	0	By definition, technician not present while sitting post-installation
4.40	* Fraction of accident leaks that are large	0.01	Calculated based on assumption that\ total probability of large leak due to an accident is approximately equal to rate of fatal injury in building construction industry: http://www.bls.gov/iif/oshwc/cfoi/worker_memorial.htm
4.41	* Probability of a leak due to an accident	0.01	Estimated to be less than the nonfatal occupational injury rate of 3% - http://www.bls.gov/iif/oshwc/osh/os/ostb3193.pdf
4.42	Probability of a leak while chiller is off while sitting post-installation	0.001	Estimated from NCI analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
Normal Operation - NO VENTILATION (generally equivalent to unoccupied hours)			
5.1	Fraction of time in normal operation without ventilation	0.422	Assumes that system is running for approximately 358 days per year with 57% ventilation runtime - based on NCI analysis of CBECS 2003 buildings with chillers - assume 100% runtime during occupied hours and runtime by CZ for off hours: 10% CZ1, 30% CZ2, 50% CZ3, 70% CZ4, 90% CZ5
5.2a	* Refrigerant leak from a 400T WC screw in a mech room during normal operation (UnitA)	0.055	From Mfr collected warranty data - Assumes 1 possible leak per unit, based on number of leaks per year expected from total population of such units. Assume even distribution of leaks (annualized)
5.2b	* Refrigerant leak from a 400T WC screw in a mech room during normal operation (UnitB)	0.055	From Mfr collected warranty data - Assumes 1 possible leak per unit, based on number of leaks per year expected from total population of such units. Assume even distribution of leaks
5.3	* Fraction of leaks that are large while chiller is off	0.001	Estimated from NCI analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
5.4	* Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
5.5	* Prob. of spark source present in a mech room during normal operation	1	Potential sources present in all mechanical rooms.
5.6	* Prob. of hot surface source present in a mech room during normal operation	0.5	Estimate based on potential presence of generator or other such hot surface source - Independent of refrigerant presence and operating state.
5.7	* Prob of boiler present in a mech room	0.2	Based on discussion with technician and strict code (E.g., ASHRAE 15) associated with locating combustion equipment and refrigerant equipment in the same mechanical room. This is likely more common in basements with smaller systems. ASHRAE 15 does not allow combustion equipment in chiller room unless combustion air is ducted in from outside air. Risk arises if ducting contains a leak and refrigerant vapor enters the combustion air ducting.
5.8	* Prob of boiler setup not to code, exposing flame	0.01	ASHRAE 15 mandates that boiler may not be present unless combustion air is ducted in from outside the mech room. Accordingly, only a boiler that is not setup to code may have exposed flame.
5.9	Prob of non-HVAC tech present in mech room during normal operation	0.005	Estimated - Independent of normal operation, servicing, installation - Assumed to be during unoccupied hours
5.14	* Fraction of time with spark > MIE and flammable concentration	0.016	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
5.15	* Fraction of time with hot surface > MIE and flammable concentration	0.005	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
5.16	* Fraction of time with flame > MIE and flammable concentration	0.29	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
5.17	* Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.006	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
5.18	* Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
5.19	* Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 due to additional deterants likely in modern workplace (e.g., signs)
5.21	* Fraction of time with lighter flame > MIE and flammable concentration	0.0004	Based on NCI Analysis for a no-mechanical-ventilation scenario (assumes infiltation only)
5.23	* Prob of exhaust ventilation malfunction during normal operation	0.00027	DOE motor TSD (Technical Support Document http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/em_preanalysis_tsdch08.pdf) indicates 10.1-12.5 year average life for 3 example NEMA Design B motors (DOE equipment Class Group 1, typical of HVAC fan motors from 1 to 500 HP). We round up to 10% failure to acount for other less likely failures such as damper motors, damper linkages, etc. Assuming 1 day of down time, we calculate 1/365*10%. May include failure of either standard speed ventilation or exhaust-speed ventilation. Assumes functioning standard (non-exhaust) ventilation - in case of complete ventilation failure, analysis assumes that personnel are notified and precautions taken because it is likely combined with failure of other major building systems.
5.24	* Monitor is broken or malfunctioning	0.05	Estimated based on discussion with technicians - may be due to lack of calibration, disabling by personnel, or malfunction. Expected lifetime is 5-7 years.
5.25	* Chiller/BMS does not self-diagnose and notify	0.8	Estimate - includes ability of communications system to transmit failure code to BMS
5.26	* Prob that technician present during normal operation	0	By definition, technician not present during normal operation

F.2 *Fault Tree Rationale Scenario B - 200T Air-cooled screw on a rooftop*

Fault Tree Rationale - 200T Air-cooled screw on a rooftop

ID		Event (*indicates that value is repeated from prior FTA branch)	Probability	Source/Discussion
Normal Operation				
1.1		Fraction of time in normal operation	0.981	Assumes that system is running for approximately 358 days per year
1.2		Refrigerant leak from a 200T AC screw on a rooftop during normal operation	0.067	From Mfr collected warranty data - Assumes 1 possible leak per unit, based on number of leaks per year expected from total population of such units. Assume even distribution of leaks (annualized)
1.3		Fraction of leaks that are large from 200T AC screw during normal operation	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
1.4		Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
1.9		Prob of non-HVAC tech present during normal operation	0.05	Estimated - Independent of normal operation, servicing, installation
1.17		Fraction of time with non-HVAC tech with source > MIE and flammable concentration	4.00E-05	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
1.18		Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
1.19		Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
1.21		Fraction of time with lighter > MIE and flammable refrig concentration	1.00E-06	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
1.25		Chiller/BMS does not self-diagnose and notify	0.8	Estimate - includes ability of communications system to transmit failure code to BMS
1.26		Prob of technician present during normal operation	0	By definition, technician not present during normal operation
Servicing				
2.1		Fraction of time spent servicing unit	0.014	Assume 5 days/yr, accounts for larger downtime some yrs for substantial teardowns, but minimal servicing some years.
2.3	*	Fraction of leaks that are large from 200T AC screw during servicing	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
2.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
2.9	*	Prob of non-HVAC tech present on rooftop during servicing	0.05	Estimated - Independent of normal operation, servicing, installation
2.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	4.00E-05	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
2.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
2.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
2.21	*	Fraction of time with lighter > MIE and flammable refrig concentration	1.00E-06	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
2.25	*	Chiller/BMS does not self-diagnose & no precautions taken	0.8	Estimate - includes ability of communications system to transmit failure code to BMS
2.26		Prob that service requires refrig transfer	0.75	Estimated based on discussions with technicians. Higher than 0.2 value from Goetzler, 1998, "Risk Assessment…" due to differences in commercial and residential systems.
2.27		Prob that service does not require refrig transfer	0.25	Time that is not associated with 2.26
2.28		Tech deliberately vents from a 200T AC screw to atmosphere	0.05	Goetzler, 1998, "Risk Assessment…"
2.29		Prob of deliberate release forming a flammable concentration	0.5	Estimated that half of deliberate releases are high volume releases
2.30		Deliberate, de minimis refrig release from a 200T AC screw during servicing	1	Assumption based on fact that technicians vent de minimis amounts during every refrigerant transfer
2.31		Prob of de minimis volume forming a flammable concentration	0	Engineering assumption based on properties of 2L refrigerants
2.32		Leak from a 200T AC screw during non-transferring servicing	0.067	Assume same as Normal Operation leaks (annual)
2.33		Leak from a 200T AC screw while transferring refrigerant during servicing	0.087	Assumed to be 2% greater likelihood than during non-transferring installation - based on Goetzler 1998
2.34		Prob that technicians checks for leaks with propane	0.01	Goetzler, 1998, "Risk Assessment…" - Reduced to 1% due to increased awareness and training since study
2.35		Likelihood of a leak in a 200T AC screw on a rooftop (total)	0.067	Assume same as Normal Operation leaks
2.36		Prob that tech does not completely evacuate refrigerant before removing pipe	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
2.37		Prob that tech unsweats brazed pipe joint	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
2.38		Prob that pipe needs removal or replacement during servicing	0.01	Estimated
2.39		Prob that technician present during servicing	1	By definition, technician present during servicing
Installation/Commissioning				
3.1		Fraction of time spent installing unit or conducting major renovations	0.0027	Includes commissioning, etc. Estimate - assume approximately 25 days per 25 years, or 1/365 per year
3.3	*	Fraction of leaks from 200T AC screws during installation that are large	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
3.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
3.9		Prob of non-HVAC tech present on rooftop during installation	0.9	Estimate - substantially higher than servicing or normal operation
3.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	4.00E-05	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
3.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
3.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
3.21	*	Fraction of time with lighter > MIE and flammable refrig concentration	1.00E-06	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
3.25		Chiller/BMS does not self-diagnose & no precautions taken	0.9	Estimated to be greater than during all normal operations because commissioning is not yet complete
3.26		Prob that installation requires refrig transfer	0.05	Estimated based on discussions with technicians - vast majority are shipped with complete charge
3.27		Prob that installation does not require refrig transfer	0.95	Time that is not associated with 3.26
3.28	*	Tech deliberately vents from a 200T AC screw to atmosphere	0.05	Goetzler, 1998, "Risk Assessment…"
3.29	*	Prob of deliberate release forming a flammable concentration	0.5	Estimated that half of deliberate releases are high volume releases
3.30	*	Deliberate, de minimis refrig release from a 200T AC screw during installation	1	Assumption based on fact that technicians vent de minimis amounts during every refrigerant transfer

Fault Tree Rationale - 200T Air-cooled screw on a rooftop				
ID		Event (*indicates that value is repeated from prior FTA branch)	Probability	Source/Discussion
3.31	*	Prob of de minimis volume forming a flammable concentration	0	Engineering assumption based on properties of 2L refrigerants
3.33		Leak from a 200T AC screw during refrig transfer during installation	0.356	Assumed to be 2% greater likelihood than during non-transferring installation - based on Goetzler 1998
3.34	*	Prob that technicians checks for leaks with propane	0.01	Goetzler, 1998, "Risk Assessment…" - Reduced to 1% due to increased awareness and training since study
3.35		Leak from a 200T AC screw during installation	0.336	From Mfr collected warranty data (annualized)
3.36	*	Prob that tech does not completely evacuate refrigerant before removing pipe	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
3.37	*	Prob that tech unsweats brazed pipe joint	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
3.38		Prob that pipe needs removal or replacement during installation	0.001	Estimate
3.39		Prob that technician present during installation	1	By definition, technician present during installation
3.40		Fraction of accident leaks that are large	0.01	Calculated based on assumption that total probability of large leak due to an accident is approximately equal to rate of fatal injury in building construction industry: http://www.bls.gov/iif/oshwc/cfoi/worker_memorial.htm
3.41		Probability of a leak due to an accident	0.01	Estimated to be less than the nonfatal occupational injury rate of 3% - http://www.bls.gov/iif/oshwc/osh/os/ostb3193.pdf
3.42		Probability of a leak while chiller is off	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
3.43		Fraction of leaks that are large while off	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
Sitting Post-Installation				
4.1		Fraction of time spent sitting post-installation	0.0270	Based on discussion with technicians and building managers, this is highly variable depending on the installation, and may be zero for some retrofit cases. Absent more concrete data, assumed to be equivalent to installation.
4.3	*	Fraction of leaks that are large while sitting post-installation	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
4.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
4.9	*	Prob of non-HVAC tech present on rooftop while sitting post-installation	0.9	Estimate - substantially higher than servicing or normal operation
4.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	4.00E-05	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
4.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
4.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
4.21	*	Fraction of time with lighter > MIE and flammable refrig concentration	1.00E-06	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
4.25	*	Chiller/BMS does not self-diagnose & no precautions taken	0.9	Estimated to be greater than during all normal operations because commissioning is not yet complete
4.39		Prob that technician present while sitting post-installation	0	By definition, technician not present while sitting post-installation
4.40	*	Fraction of accident leaks that are large	0.01	Calculated based on assumption that total probability of large leak due to an accident is approximately equal to rate of fatal injury in building construction industry: http://www.bls.gov/iif/oshwc/cfoi/worker_memorial.htm
4.41	*	Probability of a leak due to an accident	0.01	Estimated to be less than the nonfatal occupational injury rate of 3% - http://www.bls.gov/iif/oshwc/osh/os/ostb3193.pdf
4.42		Probability of a leak while chiller is off while sitting post-installation	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures

F.3 Fault Tree Rationale Scenario C - 100T Air-cooled scroll on a rooftop

Fault Tree Rationale - 100T Air-cooled scroll on a rooftop				
ID		Event (*indicates that value is repeated from prior FTA branch)	Probability	Source/Discussion
Normal Operation				
1.1		Fraction of time in normal operation	0.981	Assumes that system is running for approximately 358 days per year
1.2		Refrigerant leak from a 100T AC scroll on a rooftop during normal operation	0.034	From Mfr collected warranty data - Assumes 1 possible leak per unit, based on number of leaks per year expected from total population of such units. Assume even distribution of leaks (annualized)
1.3		Fraction of leaks that are large from 100T AC scroll during normal operation	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
1.4		Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
1.9		Prob of non-HVAC tech present during normal operation	0.05	Estimated - Independent of normal operation, servicing, installation
1.17		Fraction of time with non-HVAC tech with source > MIE and flammable concentration	3.00E-05	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
1.18		Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
1.19		Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
1.21		Fraction of time with lighter > MIE and flammable refrig concentration	1.00E-06	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
1.25		Chiller/BMS does not self-diagnose and notify	0.8	Estimate - includes ability of communications system to transmit failure code to BMS
1.26		Prob of technician present during normal operation	0	By definition, technician not present during normal operation
Servicing				
2.1		Fraction of time spent servicing unit	0.014	Assume 5 days/yr, accounts for larger downtime some yrs for substantial teardowns, but minimal servicing some years.
2.3	*	Fraction of leaks that are large from 100T AC scroll during servicing	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
2.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
2.9	*	Prob of non-HVAC tech present on rooftop during servicing	0.05	Estimated - Independent of normal operation, servicing, installation
2.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	3.00E-05	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
2.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
2.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)

Fault Tree Rationale - 100T Air-cooled scroll on a rooftop

ID		Event (*indicates that value is repeated from prior FTA branch)	Probability	Source/Discussion
2.21	*	Fraction of time with lighter > MIE and flammable refrig concentration	1.00E-06	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
2.25	*	Chiller/BMS does not self-diagnose & no precautions taken	0.8	Estimate - includes ability of communications system to transmit failure code to BMS
2.26		Prob that service requires refrig transfer	0.75	Estimated based on discussions with technicians. Higher than 0.2 value from Goetzler, 1998, "Risk Assessment…" due to differences in commercial and residential systems.
2.27		Prob that service does not require refrig transfer	0.25	Time that is not associated with 2.26
2.28		Tech deliberately vents from a 100T AC scroll to atmosphere	0.05	Goetzler, 1998, "Risk Assessment…"
2.29		Prob of deliberate release forming a flammable concentration	0.5	Estimated that half of deliberate releases are high volume releases
2.30		Deliberate, de minimis refrig release from a 100T AC scroll during servicing	1	Assumption based on fact that technicians vent de minimis amounts during every refrigerant transfer
2.31		Prob of de minimis volume forming a flammable concentration	0	Engineering assumption based on properties of 2L refrigerants
2.32		Leak during non-transferring servicing	0.034	Assume same as Normal Operation leaks (annual)
2.33		Leak while transferring refrigerant during servicing	0.054	Assumed to be 2% greater likelihood than during non-transferring installation - based on Goetzler 1998
2.34		Prob that technicians checks for leaks with propane	0.01	Goetzler, 1998, "Risk Assessment…" - Reduced to 1% due to increased awareness and training since study
2.35		Likelihood of a leak in a 100T AC scroll on a rooftop (total)	0.034	Assume same as Normal Operation leaks
2.36		Prob that tech does not completely evacuate refrigerant before removing pipe	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
2.37		Prob that tech unsweats brazed pipe joint	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
2.38		Prob that pipe needs removal or replacement during servicing	0.01	Estimated
2.39		Prob that technician present during servicing	1	By definition, technician present during servicing
Installation/Commissioning				
3.1		Fraction of time spent installing unit or conducting major renovations	0.0027	Includes commissioning, etc. Estimate - assume approximately 25 days per 25 years, or 1/365 per year
3.3	*	Fraction of leaks from 100T AC scroll during installation that are large	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
3.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
3.9		Prob of non-HVAC tech present on rooftop during installation	0.9	Estimate - substantially higher than servicing or normal operation
3.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	3.00E-05	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
3.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
3.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
3.21	*	Fraction of time with lighter > MIE and flammable refrig concentration	1.00E-06	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
3.25		Chiller/BMS does not self-diagnose & no precautions taken	0.9	Estimated to be greater than during all normal operations because commissioning is not yet complete
3.26		Prob that installation requires refrig transfer	0.05	Estimated based on discussions with technicians - vast majority are shipped with complete charge
3.27		Prob that installation does not require refrig transfer	0.95	Time that is not associated with 3.26
3.28	*	Tech deliberately vents from a 100T AC scroll to atmosphere	0.05	Goetzler, 1998, "Risk Assessment…"
3.29	*	Prob of deliberate release forming a flammable concentration	0.5	Estimated that half of deliberate releases are high volume releases
3.30	*	Deliberate, de minimis refrig release from a 100T AC scroll during installation	1	Assumption based on fact that technicians vent de minimis amounts during every refrigerant transfer
3.31	*	Prob of de minimis volume forming a flammable concentration	0	Engineering assumption based on properties of 2L refrigerants
3.33		Leak from a 100T AC scroll during refrig transfer during installation	0.195	Assumed to be 2% greater likelihood than during non-transferring installation - based on Goetzler 1998
3.34	*	Prob that technicians checks for leaks with propane	0.01	Goetzler, 1998, "Risk Assessment…" - Reduced to 1% due to increased awareness and training since study
3.35		Leak from a 100T AC scroll during installation	0.175	From Mfr collected warranty data (annualized)
3.36	*	Prob that tech does not completely evacuate refrigerant before removing pipe	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
3.37	*	Prob that tech unsweats brazed pipe joint	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
3.38		Prob that pipe needs removal or replacement during installation	0.001	Estimate
3.39		Prob that technician present during installation	1	By definition, technician present during installation
3.40		Fraction of accident leaks that are large	0.01	Calculated based on assumption that total probability of large leak due to an accident is approximately equal to rate of fatal injury in building construction industry: http://www.bls.gov/iif/oshwc/cfoi/worker_memorial.htm
3.41		Probability of a leak due to an accident	0.01	Estimated to be less than the nonfatal occupational injury rate of 3% - http://www.bls.gov/iif/oshwc/osh/os/ostb3193.pdf
3.42		Probability of a leak while chiller is off	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
3.43		Fraction of leaks that are large while off	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
Sitting Post-Installation				
4.1		Fraction of time spent sitting post-installation	0.0270	Based on discussion with technicians and building managers, this is highly variable depending on the installation, and may be zero for some retrofit cases. Absent more concrete data, assumed to be equivalent to installation.
4.3	*	Fraction of leaks that are large while sitting post-installation	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
4.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
4.9	*	Prob of non-HVAC tech present on rooftop while sitting post-installation	0.9	Estimate - substantially higher than servicing or normal operation
4.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	3.00E-05	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
4.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
4.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
4.21	*	Fraction of time with lighter > MIE and flammable concentration	1.00E-06	Based on NCI Analysis - Assumed to be 1% of the risk as calculated for the restricted air scenario
4.25	*	Chiller/BMS does not self-diagnose & no precautions taken	0.9	Estimated to be greater than during all normal operations because commissioning is not yet complete
4.39		Prob that technician present while sitting post-installation	0	By definition, technician not present while sitting post-installation

Fault Tree Rationale - 100T Air-cooled scroll on a rooftop				
ID		**Event (*indicates that value is repeated from prior FTA branch)**	**Probability**	**Source/Discussion**
4.40	*	Fraction of accident leaks that are large	0.01	Calculated based on assumption that total probability of large leak due to an accident is approximately equal to rate of fatal injury in building construction industry: http://www.bls.gov/iif/oshwc/cfoi/worker_memorial.htm
4.41	*	Probability of a leak due to an accident	0.01	Estimated to be less than the nonfatal occupational injury rate of 3% - http://www.bls.gov/iif/oshwc/osh/os/ostb3193.pdf
4.42		Probability of a leak while chiller is off while sitting post-installation	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures

F.4 Fault Tree Rationale Scenario D - 200T Air-cooled screw on a rooftop with restricted airflow

Fault Tree Rationale - 200T Air-cooled screw on a rooftop with restricted airflow				
ID		**Event (*indicates that value is repeated from prior FTA branch)**	**Probability**	**Source/Discussion**
Normal Operation				
1.1		Fraction of time in normal operation	0.981	Assumes that system is running for approximately 358 days per year
1.2		Refrigerant leak from a 200T AC screw on a rooftop during normal operation	0.067	From Mfr collected warranty data - Assumes 1 possible leak per unit, based on number of leaks per year expected from total population of such units. Assume even distribution of leaks (annualized)
1.3		Fraction of leaks that are large from 200T AC screw during normal operation	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
1.4		Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
1.9		Prob of non-HVAC tech present during normal operation	0.05	Estimated - Independent of normal operation, servicing, installation
1.17		Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.004	Based on NCI Analysis
1.18		Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
1.19		Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
1.21		Fraction of time with lighter > MIE and flammable refrig concentration	0.0001	Based on NCI Analysis
1.25		Chiller/BMS does not self-diagnose and notify	0.8	Estimate - includes ability of communications system to transmit failure code to BMS
1.26		Prob of technician present during normal operation	0	By definition, technician not present during normal operation
Servicing				
2.1		Fraction of time spent servicing unit	0.014	Assume 5 days/yr, accounts for larger downtime some yrs for substantial teardowns, but minimal servicing some years.
2.3	*	Fraction of leaks that are large from 200T AC screw during servicing	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
2.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
2.9	*	Prob of non-HVAC tech present on rooftop during servicing	0.05	Estimated - Independent of normal operation, servicing, installation
2.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.0040	Based on NCI Analysis
2.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
2.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
2.21	*	Fraction of time with lighter > MIE and flammable refrig concentration	0.0001	Based on NCI Analysis
2.25	*	Chiller/BMS does not self-diagnose & no precautions taken	0.8	Estimate - includes ability of communications system to transmit failure code to BMS
2.26		Prob that service requires refrig transfer	0.75	Estimated based on discussions with technicians. Higher than 0.2 value from Goetzler, 1998, "Risk Assessment…" due to differences in commercial and residential systems.
2.27		Prob that service does not require refrig transfer	0.25	Time that is not associated with 2.26
2.28		Tech deliberately vents from a 200T AC screw to atmosphere	0.05	Goetzler, 1998, "Risk Assessment of HFC-32 and HFC-32/134a in Split System Residential Heat Pumps"
2.29		Prob of deliberate release forming a flammable concentration	0.5	Estimated that half of deliberate releases are high volume releases
2.30		Deliberate, de minimis refrig release from a 200T AC screw during servicing	1	Assumption based on fact that technicians vent de minimis amounts during every refrigerant transfer
2.31		Prob of de minimis volume forming a flammable concentration	0	Engineering assumption based on properties of 2L refrigerants
2.32		Leak from a 200T AC screw during non-transferring servicing	0.067	Assume same as Normal Operation leaks (annual)
2.33		Leak from a 200T AC screw while transferring refrigerant during servicing	0.087	Assumed to be 2% greater likelihood than during non-transferring installation - based on Goetzler 1998
2.34		Prob that technicians checks for leaks with propane	0.01	Goetzler, 1998, "Risk Assessment…" - Reduced to 1% due to increased awareness and training since study
2.35		Likelihood of a leak in a 200T AC screw on a rooftop (total)	0.067	Assume same as Normal Operation leaks
2.36		Prob that tech does not completely evacuate refrigerant before removing pipe	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
2.37		Prob that tech unsweats brazed pipe joint	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
2.38		Prob that pipe needs removal or replacement during servicing	0.01	Estimated
2.39		Prob that technician present during servicing	1	By definition, technician present during servicing
Installation/Commissioning				
3.1		Fraction of time spent installing unit or conducting major renovations	0.0027	Includes commissioning, etc. Estimate - assume approximately 25 days per 25 years, or 1/365 per year
3.3	*	Fraction of leaks from 200T AC screw during installation that are large	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
3.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
3.9		Prob of non-HVAC tech present on rooftop during installation	0.9	Estimate - substantially higher than servicing or normal operation
3.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.0040	Based on NCI Analysis
3.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
3.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
3.21	*	Fraction of time with lighter > MIE and flammable refrig concentration	0.0001	Based on NCI Analysis

Fault Tree Rationale - 200T Air-cooled screw on a rooftop with restricted airflow				
ID		**Event (*indicates that value is repeated from prior FTA branch)**	**Probability**	**Source/Discussion**
3.25		Chiller/BMS does not self-diagnose & no precautions taken	0.9	Estimated to be greater than during all normal operations because commissioning is not yet complete
3.26		Prob that installation requires refrig transfer	0.05	Estimated based on discussions with technicians - vast majority are shipped with complete charge
3.27		Prob that installation does not require refrig transfer	0.95	Time that is not associated with 3.26
3.28	*	Tech deliberately vents from a 200T AC screw to atmosphere	0.05	Goetzler, 1998, "Risk Assessment of HFC-32 and HFC-32/134a in Split System Residential Heat Pumps"
3.29	*	Prob of deliberate release forming a flammable concentration	0.5	Estimated that half of deliberate releases are high volume releases
3.30	*	Deliberate, de minimis refrig release from a 200T AC screw during installation	1	Assumption based on fact that technicians vent de minimis amounts during every refrigerant transfer
3.31	*	Prob of de minimis volume forming a flammable concentration	0	Engineering assumption based on properties of 2L refrigerants
3.33		Leak from a 200T AC screw during refrig transfer during installation	0.356	Assumed to be 2% greater likelihood than during non-transferring installation - based on Goetzler 1998
3.34	*	Prob that technicians checks for leaks with propane	0.01	Goetzler, 1998, "Risk Assessment…" - Reduced to 1% due to increased awareness and training since study
3.35		Leak from a 200T AC screw during installation	0.336	From Mfr collected warranty data (annualized)
3.36	*	Prob that tech does not completely evacuate refrigerant before removing pipe	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
3.37	*	Prob that tech unsweats brazed pipe joint	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
3.38		Prob that pipe needs removal or replacement during installation	0.001	Estimate
3.39		Prob that technician present during installation	1	By definition, technician present during installation
3.40		Fraction of accident leaks that are large	0.01	Calculated based on assumption that total probability of large leak due to an accident is approximately equal to rate of fatal injury in building construction industry: http://www.bls.gov/iif/oshwc/cfoi/worker_memorial.htm
3.41		Probability of a leak due to an accident	0.01	Estimated to be less than the nonfatal occupational injury rate of 3% - http://www.bls.gov/iif/oshwc/osh/os/ostb3193.pdf
3.42		Probability of a leak while chiller is off	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
3.43		Fraction of leaks that are large while off	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
Sitting Post-Installation				
4.1		Fraction of time spent sitting post-installation	0.0270	Based on discussion with technicians and building managers, this is highly variable depending on the installation, and may be zero for some retrofit cases. Absent more concrete data, assumed to be equivalent to installation.
4.3	*	Fraction of leaks that are large while sitting post-installation	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
4.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
4.9	*	Prob of non-HVAC tech present on rooftop while sitting post-installation	0.9	Estimate - substantially higher than servicing or normal operation
4.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.004	Based on NCI Analysis
4.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
4.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
4.21	*	Fraction of time with lighter > MIE and flammable concentration	0.0001	Based on NCI Analysis
4.25	*	Chiller/BMS does not self-diagnose & no precautions taken	0.9	Estimated to be greater than during all normal operations because commissioning is not yet complete
4.39		Prob that technician present while sitting post-installation	0	By definition, technician not present while sitting post-installation
4.40	*	Fraction of accident leaks that are large	0.01	Calculated based on assumption that total probability of large leak due to an accident is approximately equal to rate of fatal injury in building construction industry: http://www.bls.gov/iif/oshwc/cfoi/worker_memorial.htm
4.41	*	Probability of a leak due to an accident	0.01	Estimated to be less than the nonfatal occupational injury rate of 3% - http://www.bls.gov/iif/oshwc/osh/os/ostb3193.pdf
4.42		Probability of a leak while chiller is off while sitting post-installation	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures

F.5 Fault Tree Rationale Scenario E - 100T Air-cooled scroll on a rooftop with restricted airflow

Fault Tree Rationale - 100T Air-cooled scroll on a rooftop with restricted airflow				
ID		**Event (*indicates that value is repeated from prior FTA branch)**	**Probability**	**Source/Discussion**
Normal Operation				
1.1		Fraction of time in normal operation	0.981	Assumes that system is running for approximately 358 days per year
1.2		Refrigerant leak from a 100T AC scroll on a rooftop during normal operation	0.034	From Mfr collected warranty data - Assumes 1 possible leak per unit, based on number of leaks per year expected from total population of such units. Assume even distribution of leaks (annualized)
1.3		Fraction of leaks that are large from 100T AC scroll during normal operation	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
1.4		Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
1.9		Prob of non-HVAC tech present during normal operation	0.05	Estimated - Independent of normal operation, servicing, installation
1.17		Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.003	Based on NCI Analysis
1.18		Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
1.19		Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
1.21		Fraction of time with lighter > MIE and flammable concentration	0.0001	Based on NCI Analysis
1.25		Chiller/BMS does not self-diagnose and notify	0.8	Estimate - includes ability of communications system to transmit failure code to BMS
1.26		Prob of technician present during normal operation	0	By definition, technician not present during normal operation
Servicing				
2.1		Fraction of time spent servicing unit	0.014	Assume 5 days/yr, accounts for larger downtime some yrs for substantial teardowns, but minimal servicing some years.

Fault Tree Rationale - 100T Air-cooled scroll on a rooftop with restricted airflow				
ID		**Event (*indicates that value is repeated from prior FTA branch)**	**Probability**	**Source/Discussion**
2.3	*	Fraction of leaks that are large from 100T AC scroll during servicing	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
2.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
2.9	*	Prob of non-HVAC tech present on rooftop during servicing	0.05	Estimated - Independent of normal operation, servicing, installation
2.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.0030	Based on NCI Analysis
2.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
2.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
2.21	*	Fraction of time with lighter > MIE and flammable concentration	0.0001	Based on NCI Analysis
2.25	*	Chiller/BMS does not self-diagnose & no precautions taken	0.8	Estimate - includes ability of communications system to transmit failure code to BMS
2.26		Prob that service requires refrig transfer	0.75	Estimated based on discussions with technicians. Higher than 0.2 value from Goetzler, 1998, "Risk Assessment…" due to differences in commercial and residential systems.
2.27		Prob that service does not require refrig transfer	0.25	Time that is not associated with 2.26
2.28		Tech deliberately vents from a 100T AC scroll to atmosphere	0.05	Goetzler, 1998, "Risk Assessment…"
2.29		Prob of deliberate release forming a flammable concentration	0.5	Estimated that half of deliberate releases are high volume releases
2.30		Deliberate, de minimis refrig release from a 100T AC scroll during servicing	1	Assumption based on fact that technicians vent de minimis amounts during every refrigerant transfer
2.31		Prob of de minimis volume forming a flammable concentration	0	Engineering assumption based on properties of 2L refrigerants
2.32		Leak from a 100T AC scroll during non-transferring servicing	0.034	Assume same as Normal Operation leaks (annual)
2.33		Leak from a 100T AC scroll while transferring refrigerant during servicing	0.054	Assumed to be 2% greater likelihood than during non-transferring installation - based on Goetzler 1998
2.34		Prob that technicians checks for leaks with propane	0.01	Goetzler, 1998, "Risk Assessment…" - Reduced to 1% due to increased awareness and training since study
2.35		Likelihood of a leak in a 100T AC scroll on a rooftop (total)	0.034	Assume same as Normal Operation leaks
2.36		Prob that tech does not completely evacuate refrigerant before removing pipe	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
2.37		Prob that tech unsweats brazed pipe joint	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
2.38		Prob that pipe needs removal or replacement during servicing	0.01	Estimated
2.39		Prob that technician present during servicing	1	By definition, technician present during servicing
Installation/Commissioning				
3.1		Fraction of time spent installing unit or conducting major renovations	0.0027	Includes commissioning, etc. Estimate - assume approximately 25 days per 25 years, or 1/365 per year
3.3	*	Fraction of leaks from 100T AC scroll during installation that are large	0.05	From discussion with technicians - represents ~1 in 20 leaks being large - Same for any state of operation
3.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
3.9		Prob of non-HVAC tech present on rooftop during installation	0.9	Estimate - substantially higher than servicing or normal operation
3.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.0030	Based on NCI Analysis
3.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
3.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
3.21	*	Fraction of time with lighter > MIE and flammable refrig concentration	0.0001	Based on NCI Analysis
3.25		Chiller/BMS does not self-diagnose & no precautions taken	0.9	Estimated to be greater than during all normal operations because commissioning is not yet complete
3.26		Prob that installation requires refrig transfer	0.05	Estimated based on discussions with technicians - vast majority are shipped with complete charge
3.27		Prob that installation does not require refrig transfer	0.95	Time that is not associated with 3.26
3.28	*	Tech deliberately vents from a 100T AC scroll to atmosphere	0.05	Goetzler, 1998, "Risk Assessment…"
3.29	*	Prob of deliberate release forming a flammable concentration	0.5	Estimated that half of deliberate releases are high volume releases
3.30	*	Deliberate, de minimis refrig release from a 100T AC scroll during installation	1	Assumption based on fact that technicians vent de minimis amounts during every refrigerant transfer
3.31	*	Prob of de minimis volume forming a flammable concentration	0	Engineering assumption based on properties of 2L refrigerants
3.33		Leak from a 100T AC scroll during refrig transfer during installation	0.195	Assumed to be 2% greater likelihood than during non-transferring installation - based on Goetzler 1998
3.34	*	Prob that technicians checks for leaks with propane	0.01	Goetzler, 1998, "Risk Assessment…" - Reduced to 1% due to increased awareness and training since study
3.35		Leak from a 100T AC scroll during installation	0.175	From Mfr collected warranty data (annualized)
3.36	*	Prob that tech does not completely evacuate refrigerant before removing pipe	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
3.37	*	Prob that tech unsweats brazed pipe joint	0.05	Goetzler, 1998, "Risk Assessment…" Equivalent to value for 'Tech lacks training or proper equipment"
3.38		Prob that pipe needs removal or replacement during installation	0.001	Estimate
3.39		Prob that technician present during installation	1	By definition, technician present during installation
3.40		Fraction of accident leaks that are large	0.01	Calculated based on assumption that total probability of large leak due to an accident is approximately equal to rate of fatal injury in building construction industry: http://www.bls.gov/iif/oshwc/cfoi/worker_memorial.htm
3.41		Probability of a leak due to an accident	0.01	Estimated to be less than the nonfatal occupational injury rate of 3% - http://www.bls.gov/iif/oshwc/osh/os/ostb3193.pdf
3.42		Probability of a leak while chiller is off	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
3.43		Fraction of leaks that are large while off	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
Sitting Post-Installation				
4.1		Fraction of time spent sitting post-installation	0.0270	Based on discussion with technicians and building managers, this is highly variable depending on the installation, and may be zero for some retrofit cases. Absent more concrete data, assumed to be equivalent to installation.
4.3	*	Fraction of leaks that are large while sitting post-installation	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures
4.4	*	Refrigerant is flammable	1	Assumed based on existence of flammability limits. Under certain conditions, for certain 2L refrigerants, this may not be true - represents most conservative case.
4.9	*	Prob of non-HVAC tech present on rooftop while sitting post-installation	0.9	Estimate - substantially higher than servicing or normal operation
4.17	*	Fraction of time with non-HVAC tech with source > MIE and flammable concentration	0.003	Based on NCI Analysis

Fault Tree Rationale - 100T Air-cooled scroll on a rooftop with restricted airflow

ID		Event (*indicates that value is repeated from prior FTA branch)	Probability	Source/Discussion
4.18	*	Fraction of people who smoke	0.3	Goetzler, 1998, "Risk Assessment…" - reduced from 0.4 due to reductions in smoking in years since this study.
4.19	*	Fraction of people who lack or ignore training	0.05	Goetzler, 1998, "Risk Assessment…" - modified from 0.1 to account for additional deterants likely in modern workplace (signs, common sense, etc)
4.21	*	Fraction of time with lighter > MIE and flammable concentration	0.0001	Based on NCI Analysis
4.25	*	Chiller/BMS does not self-diagnose & no precautions taken	0.9	Estimated to be greater than during all normal operations because commissioning is not yet complete
4.39		Prob that technician present while sitting post-installation	0	By definition, technician not present while sitting post-installation
4.40	*	Fraction of accident leaks that are large	0.01	Calculated based on assumption that total probability of large leak due to an accident is approximately equal to rate of fatal injury in building construction industry: http://www.bls.gov/iif/oshwc/cfoi/worker_memorial.htm
4.41	*	Probability of a leak due to an accident	0.01	Estimated to be less than the nonfatal occupational injury rate of 3% - http://www.bls.gov/iif/oshwc/osh/os/ostb3193.pdf
4.42		Probability of a leak while chiller is off while sitting post-installation	0.001	Estimated from TIAX analysis due to absence of vibrations or other mechanically imparted forces which can induce component failures