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Integrated Energy Systems

Hazards and Probabilistic Risk Assessments of Advanced Reactors Coupled with Industrial Facilities

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EXECUTIVE SUMMARY

This report provides a roadmap and tool kit for site specific risk assessments across a broad range of industrial customers co-located with advanced nuclear power plants (ANPP) that are not currently built and operating in the U.S. This report builds upon the body of work sponsored by the Department of Energy (DOE) Integrated Energy Systems Pathway that has produced industrial requirements studies and techno-economic assessments on the topics of feasibility of ANPP supported industrial processes. This report also leverages the DOE Light Water Reactor Sustainability (LWRS) program that has presented hazards assessment and generic probabilistic risk assessments (PRAs) for the addition of a heat extraction system (HES) to light-water reactors (LWRs) co-located with hydrogen production facilities [1]. Many of the hazard assessments and risk assessments performed for the LWRS report are agnostic to whether the nuclear reactor is an ANPP or were adapted to the ANPP focus. The report performs hazards assessments to include industrial facilities: an oil refinery, a methanol plant, a synthetic fuel (synfuel) plant, the production of synthetic gas (syngas) as part of the methanol and synfuel plants, wood pulp and paper mills, and hydrogen production [2]. Hydrogen production facilities are assessed in depth through prior reports in the LWRS program and the results are leveraged in this report. All these facilities are specified through industrial process and requirements research performed by national laboratories, universities, and interaction with industry. Many of the processes used in this report are pre-conceptual designs to use for decarbonization of the current technology facilities. A process of failure modes and effects analysis (what can go wrong) and accidentology (what has historically gone wrong) was used to determine the hazards presented to the nuclear power plant by the addition of the HES and the industrial customer. Chemical properties of feedstocks and products are summarized as part of the hazards assessment. Example analysis procedures are provided for each of the hazard types identified. These deterministic analyses can be used to assess adherence to licensing criteria. They can also be used to meet other safety goals like protection of the public, workers, or industrial facility equipment. A modular high temperature gas-cooled reactor (MHTGR) PRA only existing on paper was modeled and verified in modern PRA software. This will provide a tool for representative ANPP probabilistic analyses for future research.

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ACRONYMS

AFW	auxiliary feedwater
ALOHA	Areal Locations of Hazardous Atmospheres
ANPP	Advanced nuclear power plant
ARIA	Analysis, Research and Information on Accidents
ATE	acute toxicity estimate
ATWS	anticipated transient without scram
Bauwens	Bauwens-Dorofeev hydrogen jet leak detonation consequence methodology
BESS	battery energy storage system
BLEVE	boiling liquid expanding vapor explosion
BST	Baker-Strehlow-Tang detonation consequence methodology
BWR	boiling-water reactor
CSB	Chemical Safety and Hazard Investigation Board
CST	condensate storage tanks
DDT	deflagration to detonation transition
DOE	U.S. Department of Energy
DRA	deterministic risk assessment
DRACS	direct reactor auxiliary cooling systems
EPA	Environmental Protection Agency
ET	event tree
FMEA	failure modes and effects analysis
FPP	fire protection plan
FST	finished short tons
FT	fault tree
HES	heat extraction system, synonym for HTS
HTEF	high-temperature electrolysis facility
HTF	heat-transfer fluid
HTS	heat transfer system, synonym for HES
IE	initiating event
INL	Idaho National Laboratory
LAR	licensing amendment review
LOOP	loss-of-offsite power
LWR	light-water reactor
LWRS	Light Water Reactor Sustainability program

MSIV	main steam isolation valves, akin to thermal loop isolation valves in ANPPs
NFPA	National Fire Protection Association
NPP	LWR nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OCA	owner-controlled area
OSHA	Occupational Safety and Health Administration
P&ID	piping and instrumentation diagram
PAC	Protective Action Criteria
PRA	probabilistic risk assessment
PWR	pressurized-water reactor
RCCS	reactor cavity cooling system
RPN	risk priority number
RWGS	reverse water gas shift
RVACS	reactor vessel auxiliary cooling system
S&L	Sargent and Lundy company
SAPHIRE	Systems Analysis Programs for Hands-on Integrated Reliability Evaluations
SME	subject matter expert
SNL	Sandia National Laboratories
SOEC	solid oxide electrolysis cells
SSC	structures, systems, and components
STEL	short-term exposure limit
synfuel	Synthetic fuel (sustainable, non-fossil fuel-based fuels)
syngas	synthesis gas, a mixture of carbon monoxide and hydrogen
TWA	time-weighted average
VCE	vapor cloud explosions

Integrated Energy Systems

Hazards and Probabilistic Risk Assessments of Advanced Reactors Coupled with Industrial Facilities

1. INTRODUCTION

1.1 Nuclear-Supported Industrial Facilities

The U.S. electric power grid continues to evolve resulting in an emerging gap between the growth of non-dispatchable renewable energy generation and lagging clean energy storage that continues to contribute to the unproductive expansion of time-of-day excess clean energy generation. The overlapping impact of and competition between the dominant clean-generating sources (intermittent renewables and baseload nuclear power) exacerbates this challenge during daily supply-and-demand cycles.

A contributing factor is that both intermittent renewables and baseload nuclear power have inherent flexibility constraints in their operational models. Nuclear power has significant near-term potential to change its long-standing operational model by shifting generation output away from electrical generation when there is no additional grid demand for clean energy. New installations of ANPPs look to take advantage of direct connection to industrial facilities as a primary customer, not yet burdened with the designation of being a baseload provider. Even if considered a baseload provider, nuclear could directly, or flexibly, produce real-time usable or storable clean energy to decarbonizing functions across the power, industrial, and transportation sectors. Nuclear generated electrical and/or thermal energy can be used in many industrial processes beyond producing hydrogen. These industrial applications include decarbonization of oil refinery processes, producing methanol for synfuel production, and decarbonization of wood pulp and paper mills.

The U.S. Department of Energy's (DOE) support under the Integrated Energy Systems (IES) Program at Idaho National Laboratory (INL) is accelerating key technology development in this area. The current IES research and development focus regarding implementation of nuclear thermal and electrical energy support of industrial processes is being addressed through exploration of practical pre-conceptual designs of thermal extraction and delivery, techno-economic assessments to determine the feasibility and cost effectiveness, and the safety and licensing success paths consistent with the United States Nuclear Regulatory Commission (NRC) requirements.

Figure 1-1. Nuclear can provide heat and electricity for many industrial processes.

This report has been developed as a key element of the FPOG Pathway program to support utility assessment of essential aspects for licensing approval of proposed modifications that facilitate thermal energy extraction from the nuclear power plant and provide electrical power to supply co-located industrial processes that provide for nuclear plant operational flexibility for economic value and decarbonization. Specifically, this report provides guidance for utilities for both hazards analysis and for the Probabilistic Risk Assessment (PRA) evaluation required as part of site licensing and modification of licensed ANPP designs.

For NRC approval of an ANPP used to support an industrial process where there is direct coupling of the ANPP to the industrial facility or where there is construction within the ANPP's owner control area, a documentation is required that the ANPP safety will not be adversely affected. The following assembles hazard analyses that support the ANPP safety case. The identified hazards provide input to the PRA model of an ANPP and industrial facilities. The fragility of the ANPP structures, systems, and components (SSCs) combined with deterministic consequence analysis were used to risk-inform the safe separation distance of the individual facilities from the ANPP's SSCs. Procedures were investigated for setting the safe separation distance between the ANPP and the industrial facility including the adherence to the ANPP site fire protection plan and underlying code/licensing requirements. A deterministic approach was proposed for use to set the safe separation distance by using the criteria in U.S. Nuclear Regulatory Commission's (NRC) Regulation Guide 1.91 [3] even within the ANPP's owner-controlled area (OCA) where it is not formally required. Modifications to the ANPP and external hazards from each facility were considered.

A modular high temperature gas reactor (MNPP) was modeled in current state of the art PRA software in preparation for further development of PRA analysis in future work.

1.2 Risk Assessment Roles in Safety and Licensing of Nuclear Power Plant Modifications

For direct coupling and siting to an industrial customer to be approved, the ANPP prospective licensees must demonstrate that ANPP safety will not be adversely affected. This will most likely be accomplished in the details of a final safety analysis report for approval by the NRC. Both deterministic risk assessment (DRA) and probabilistic risk assessment (PRA) are used to risk-inform the site license application.

DRA sets criteria for safe siting distance between an ANPP and an industrial facility. DRA also informs the inputs to the PRA. Hazards to the ANPP presented by industrial processes are quantified through deterministic analyses. The hazard's effects versus distance are critical inputs for determining safe siting distance between the facilities.

Examples of DRA used for ANPPs co-located with industrial facilities are blast overpressure, heat flux from fires, and concentrations of toxic chemical clouds.

PRA is a process by which risk is numerically estimated by computing the probabilities of what can go wrong and the consequences of those undesired events. The accident occurrence frequency to the probability of the ANPP mitigating the accident without fuel damage are all quantified through PRA. The quantitative PRA results are compared to U.S. Code of Federal Regulations and NRC guidelines which determine if the design and operation are safe enough for approval or if changes need to be made to increase its safety.

An advanced reactor PRA determines frequency and consequences of the resultant release categories caused by the failure of reactor control and safety systems. The Non-Light Water Reactor PRA Standard [4] and NEI 18-04 [5] are two of the guiding documents that determine the build and use of the results of the PRA to verify the safety of the ANPP design located at the site and its use. The ASME/ANS document [4] is the standard for hazards assessment and building the PRA to quantify the frequency of occurrence of radiological release categories. The NEI 18-04 frequency–consequence (F-C) curve (Figure 1-2) provides a recommendation of goals based on these frequencies and the consequences of the release category source terms. The NEI 18-04 F-C curve is based off of top level safety targets. Frequency targets include the definition of the frequency of occurrences of Anticipated Operational Occurrences, Design Basis Events, and Beyond Design Basis Events for the frequencies. Consequence targets consist of codes and standards for radiation dosage at the identified exclusion boundary of the ANPP.

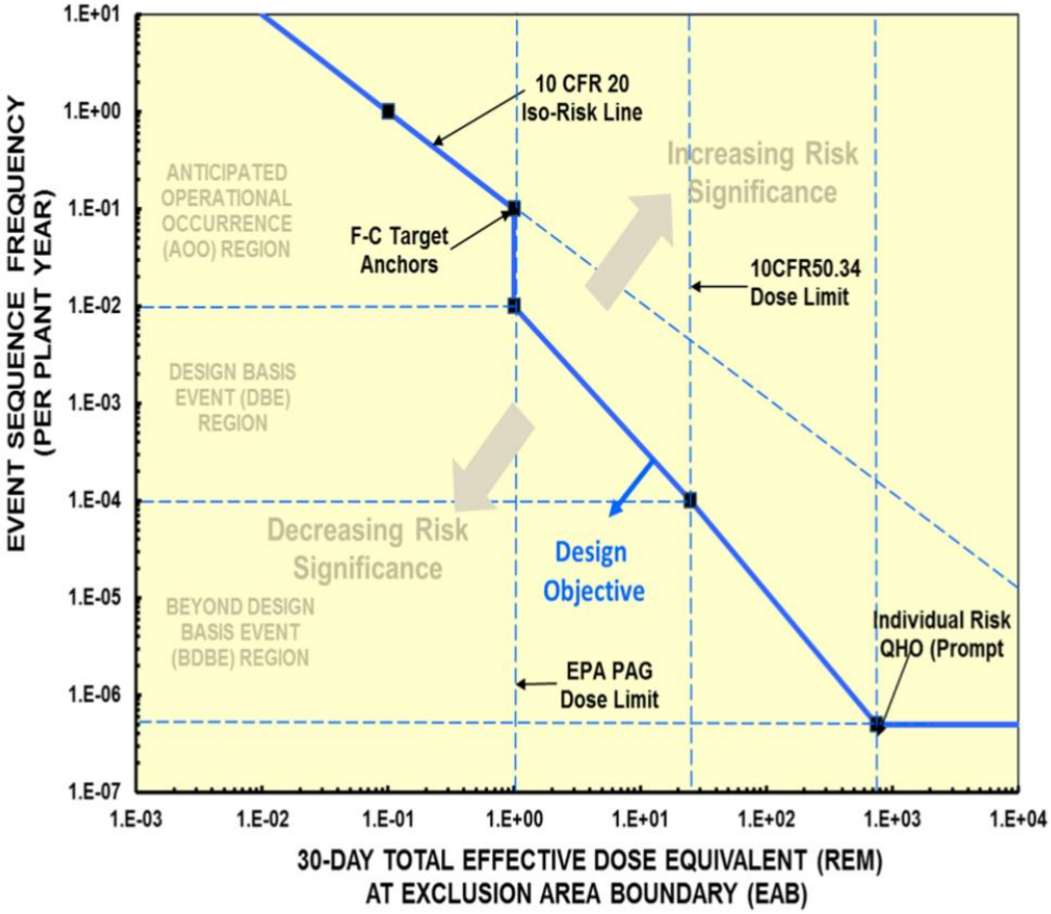


Figure 1-2. NEI 18-04 Frequency – Consequence Curve

Traditionally, top-down methods are used to define initiating event (IE) frequencies by using data of recorded events to calculate the event frequency. When there is a lack of recorded events as is true in most cases of new advanced reactor designs it is necessary to use a bottom-up method to calculate the initiating event frequency.

The bottom-up method for initiating event frequency and the probability of failure for fault tree (FT) top events rely on knowing the design system componentry and controls that are then translated into a FT. Typically, this is accomplished by referencing a system piping and instrumentation diagram (P&ID) and a list of operator actions, then identifying how each of those components and actions could fail in a way that leads to an IE or a mitigating failure event in the event tree (ET). The FTs are created and integrated into ETs by identifying within which IE the system failure would be used, either as an initiator itself or as a modification to one of the responding systems.

2. PROJECT SCOPE

The scope of this report is to assess hazards and consequences presented by representative industrial customer facilities located near an ANPP. Hazards analysis is performed using accidentology and failure modes and effects analysis (FMEA). The research uses the representative industrial facilities (industrial customers) to perform a hazards analysis and facility siting analysis. The hazards analyses for these facilities provide quantitative input to the PRA of the ANPP and deterministic quantifications used for safe separation distance siting analysis. The quantitative results from the deterministic analyses and the qualitative results from the FMEA are used to assess the risk to the local community and the economics of the ANPP. Safe separation standoff distances between the ANPP and the industrial customer are discussed, and regulations and codes are provided for determining them.

External events are assessed to determine if any of their effects on the industrial facility will affect the ANPP.

Hazards of storage of industrial feedstock and products are also assessed, and a standoff distance calculation method is presented for assessment of acceptable risk to the ANPP.

Since there are no generic ANPP PRAs available for hazards assessments, a national laboratory MHTGR model that only existed on paper was modeled in a modern PRA software. This model will be used in future studies for assessment of thermal extraction systems and more.

3. SPECIFICATIONS OF THE SUPPORTED INDUSTRIAL FACILITIES

Various industrial facilities were analyzed for integration with an ANPP. The ANPP can supply thermal and/or electrical energy to support the operation of the facility. The following sections describe these facilities and Table 3-1 shows a summary of the requirements of the various analyzed industrial facilities. The hydrogen High-Temperature Electrolysis Facility (HTEF) is analyzed at three different system capacities as shown in the table. The petroleum refinery thermal requirement includes both the heat from combustion (446 MWt) and steam (39 MWt). All other thermal power requirements are supplied by steam.

Table 3-1. Overview of industrial facility requirements.

Process	Reference	Plant Size (/day)	Thermal Req. (MWt)	Electrical Req. (MWe)
H_2 High-Temperature Electrolysis Facility	[6]	54 MT	25	105 (100 MW_{nom})
		272 MT	105	500
		544 MT[a]	205[a]	1000[a]
Methanol Plant	[7]	1,340 MT	-19.7[b]	24
Synthetic Fuel Production (Methanol Intermediary)	[7]	4,600 BBL	156	26
Synthetic Fuel Production (F-T)	[8]	4,405 BBL	73 (for HTEF)	437 (422 HTEF, 15 F-T)
Petroleum Refinery	[2]	100,000 BBL	485	28
Pulp and Paper Mill	[2]	1095 finished short tons (FST)	156	25

a. Assumes two adjacent ANPP unit-connected 500 MW_{nom} functioning in parallel as a single common facility with the same losses and margin.

b. 19.7 MWt generated, no thermal input is required.

3.1 High Temperature Electrolysis Hydrogen Facility

Production of hydrogen from electrolysis using solid oxide electrolysis cells (SOECs) or through proton exchange membrane processes is the most promising large-scale carbon-free method of producing hydrogen. The efficiency advantages of SOEC HTEFs make them more desirable when steam and electricity are both supplied. The ANPP's ability to directly supply both electrical energy and thermal energy for process steam production without carbon emissions makes it ideal for this application. This report concentrates on SOEC HTEF designs. Preconceptual hydrogen HTEFs [1] specifications come from designs that are rated as 100 MW_{nom} and 500 MW_{nom} [6]. The 1000 MW_{nom} plant is assumed to be two adjacent 500 MW_{nom} facilities, therefore doubling the 500 MW_{nom} HTEF requirements. The electrical requirements match the nominal energy of the HTEFs, while the thermal requirements are 25, 105, and 205 MWt respectively.

3.2 Methanol Plant

Methanol is a valuable product because it has a wide variety of applications as a feedstock, such as for synthetic fuel production, as well as an end-use product. Currently, more than 85% of global methanol is synthesized from coal gasification and steam methane reforming [9]. These methods rely on coal or natural gas feedstocks to react with steam to form synthesis gas (syngas) which is a mixture of carbon monoxide and hydrogen. Syngas is then used to create methanol. Utilizing hydrogen generated via electrolysis and captured carbon dioxide process through selexol filtration, reduces the associated greenhouse gas emissions compared with the production of methanol generated with coal or natural gas-based feedstocks [2]. This methodology utilizing electrolysis and carbon capture is analyzed in this report. The process and its requirements will be explained below.

The reverse water gas shift (RWGS) reaction generates the syngas which is used to produce the methanol in a series of fixed bed reactors [2]. The base plant size for reference utilized from [7] is 1,340 metric tons of methanol per day. This was determined from coupling with a 500 MW ANPP. The thermal and electrical requirements are -19.7 MWt and 24 MWe, respectively, based off the methanol synthesis portion of an overall synfuel synthesis process. Values may be slightly higher than a standalone methanol synthesis facility. The thermal requirement is negative because the process generates 19.7 MWt. More about this process and the requirements can be found in [7].

3.3 Synthetic Fuel Production

Synthetic fuel (synfuel) is another valuable commodity. It is created using renewable feedstocks of hydrogen and carbon dioxide which significantly decrease the carbon usage compared to other fossil fuels such as petroleum and natural gas. The carbon dioxide used is captured from the atmosphere, neutralizing the net carbon associated with the process.

Two methods of synfuel production are considered in this analysis: production of synfuel with methanol as an intermediary product and the traditional Fischer-Tropsch process. Each of these processes share the same selexol-based carbon dioxide capture and RWGS reaction to create syngas from the carbon dioxide and hydrogen feeds, but the synthesis process differs. These two methods and their requirements are described in the following sub-sections.

These two methods also share the same final stages of fuel production as a traditional oil refinery. These are the separation and distillation, conversion through hydro-cracking, and tail gas utilization processes [7] as highlighted in Figure 3-1. For this reason, the hazards and accidentology for synfuel production are represented by analysis on refineries and are not repeated in the synfuel section. Combining the analyses of methanol production with the analyses of the common stages of the oil refinery result in an analysis of synfuel production plants.

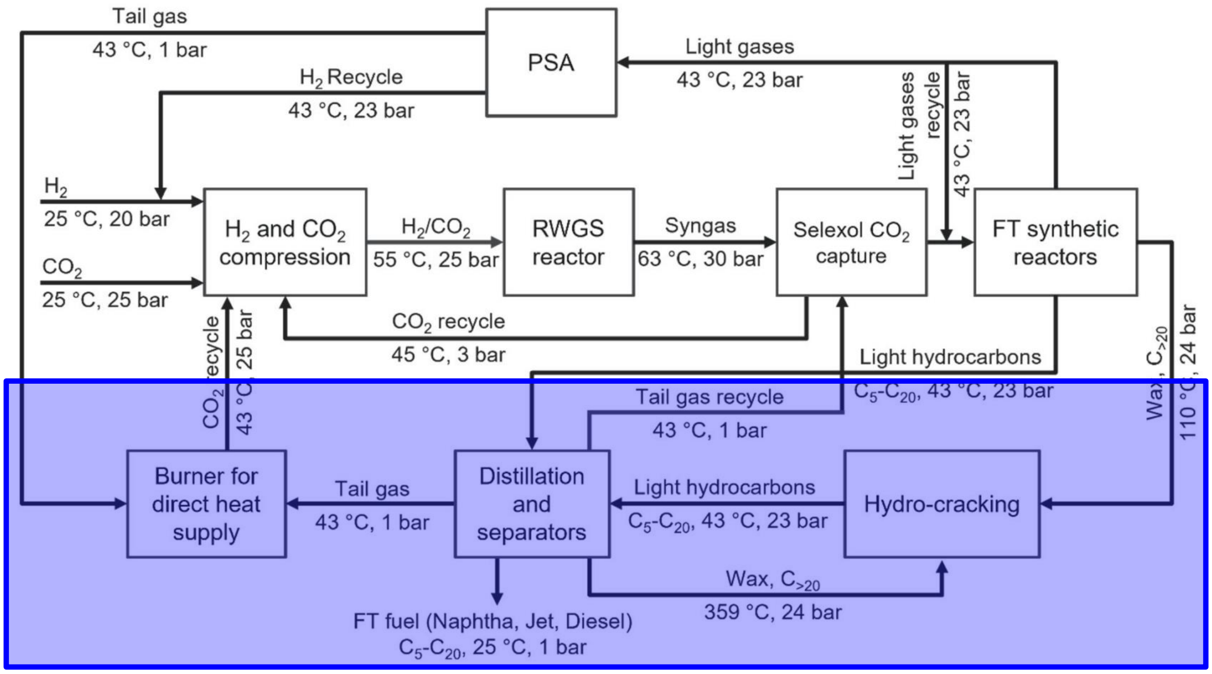


Figure 3-1. Synthetic fuel production process flow, highlighting the final stages that are similar to a traditional oil refinery [7].

3.3.1 Intermediary Methanol Product in Synthetic Fuel Plant

This method leverages methanol as an intermediary feedstock for synfuel production. Therefore, the process of synfuel production analyzed begins by using the methodology for methanol production explained above. Then, the methanol is converted into light olefins, primarily ethylene, propylene, and a minor amount of butene, then oligomerized into higher carbon length olefins. This results in a mixture of olefins that are mostly diesels. Finally, hydrogenation of the olefins are saturated into corresponding paraffins which are then separated within a fractionation unit to result in the following synfuels: naptha, jet fuel, and diesel.

The base plant size, for reference, produced 4,600 barrels of synfuel per day [7]. This was determined from coupling with a 500 MW ANPP. The thermal and electrical requirements are 156 MWt and 26 MWe, respectively. Thermal power requirements can be delivered in the form of steam. More about this process and the requirements can be found in [7].

3.3.1 Fischer-Tropsch Process in Synthetic Fuel Plant

A reference Fischer-Tropsch (F-T) synfuel synthesis facility was adopted from a previous study [8]. The facility requires 255 MT/day H_2 and 1,580 MT/day CO_2 to produce 4,405 barrels of synfuel per day. The hydrogen feedstock is produced by an onsite HTEF with electricity consumption of 39.8 kWh/kg, resulting in an electricity demand from the ANPP at 422 MWe. The HTEF requires thermal steam energy of 6.86 kWh/kg, resulting in a thermal demand of 73 MWt from the ANPP. This hydrogen feedstock could be supplied from a 500 MW_{nom} HTEF. The F-T synthesis itself does not require ANPP steam, but it requires a 15 MWe power supply. Therefore, the combined power drawn from the ANPP is 437 MWe.

3.4 Petroleum Refinery

There are many products of a typical petroleum refinery and the decarbonization efforts are focused on the carbon dioxide produced when creating these products, not the reduction of carbon from when the products are used. Petroleum refineries are major contributors of carbon dioxide in industry. In a reference refinery plant using 100 thousand barrels per day [2], a total of 1.59 MT of carbon dioxide is generated. The reference refinery plant uses natural gas as a feedstock to provide heat and power to crack the crude oil and generate useful products such as asphalt, gasoline, diesel, and jet fuel. By integrating the refinery with an ANPP, the usage of natural gas can be significantly reduced. The thermal requirement includes both the heat from combustion (446 MWt) and steam (39 MWt). The electrical requirement for a reference refinery is 28 MWe.

3.5 Pulp and Paper Mill

Paper in specific forms has a persisting and growing demand. Integrating with nuclear could be a way to ensure stability and growth over time. For this analysis, kraft pulping was chosen as the type of processing used because it currently makes up 80% of the total chemical pulping industry worldwide [10]. This pulping process includes dissolution of the wood chips liquor or chemical solutions to create a pulp product which can be processed into paper products. First, a white liquor solution is used to digest wood chips. Then the pulp is separated from the used cooking liquor and further refined via defibrating and bleaching stages if required to prepare the pulp for processing into paper products. The strength of the kraft process is the recycling of the liquors and heat through multiple stages. The spent cooking liquor is combined with pulp wash to create a black liquor. This is fired to recover heat for the pulping process. The inorganic chemicals of the black liquor are collected and dissolved in water to form a green liquor. Later, it is transferred to a causticizing tank to convert the solution back to white liquor for use in the digestion step again. For reference, the base plant size utilized from [2] is approximately 1,095 FST of paper product. The thermal and electrical requirements are 156 MWt and 25 MWe, respectively. Thermal power requirements can be delivered in the form of steam. More about this process and the requirements can be found in [2].

4. NUCLEAR POWER PLANT MODIFICATIONS FOR AN INDUSTRIAL CUSTOMER

There are two ANPP system modifications proposed. The first is adding the HES to extract thermal power and provide it to the industrial customer. The second is adding components to the switchyard necessary to provide direct electrical coupling to the industrial customer. Not all industrial customers will choose to use both thermal and electrical energy sources. Hydrogen HTEFs will use both, but it is at other industrial facility's discretion to choose what energy sources delivery to use from the ANPP. The specifications below assume that both energy sources are required from the ANPP.

4.1 Nuclear Power Plant with Heat Extraction System

The LWRS report released concurrently to this report examines some fully specified steam to steam HESs for three different power levels for LWRs, described specifically for different nominal power capacities of hydrogen HTEFs in [1] and by thermal capacities in Reference [11]. Some of this design information may be of use to an ANPP HES design. Please refer to [1] or [11] for more information.

Preliminary work has been performed for the beginnings of HES designs for ANPPs. None of them are currently specified enough to include in a PRA so this is a research goal for next fiscal year. An example proposed design is provided in the following paragraphs.

A study by INL proposed a preliminary heat extraction system for utilizing HTGR heat for a refinery process [12]. It references integration with an Xe-100 HTGR which operates at a lower power, thermal and electrical, than the MHTGR modeled in this document's PRA, but enough to cover steam and power requirements for the same reference refinery process. Heat transfer is achieved by a combined heat and power (CHP) system which utilizes an intermediate heat exchanger system to superheat steam for the refinery with the HTGR secondary steam heat as well as provides process steam and steam for an associated HTSE. The process flow diagram for the entire CHP system and its connections to the existing HTGR and refinery is shown in Figure 4-1 and the focus on the HES (heat transfer system in the drawings) is shown in Figure 4-2.

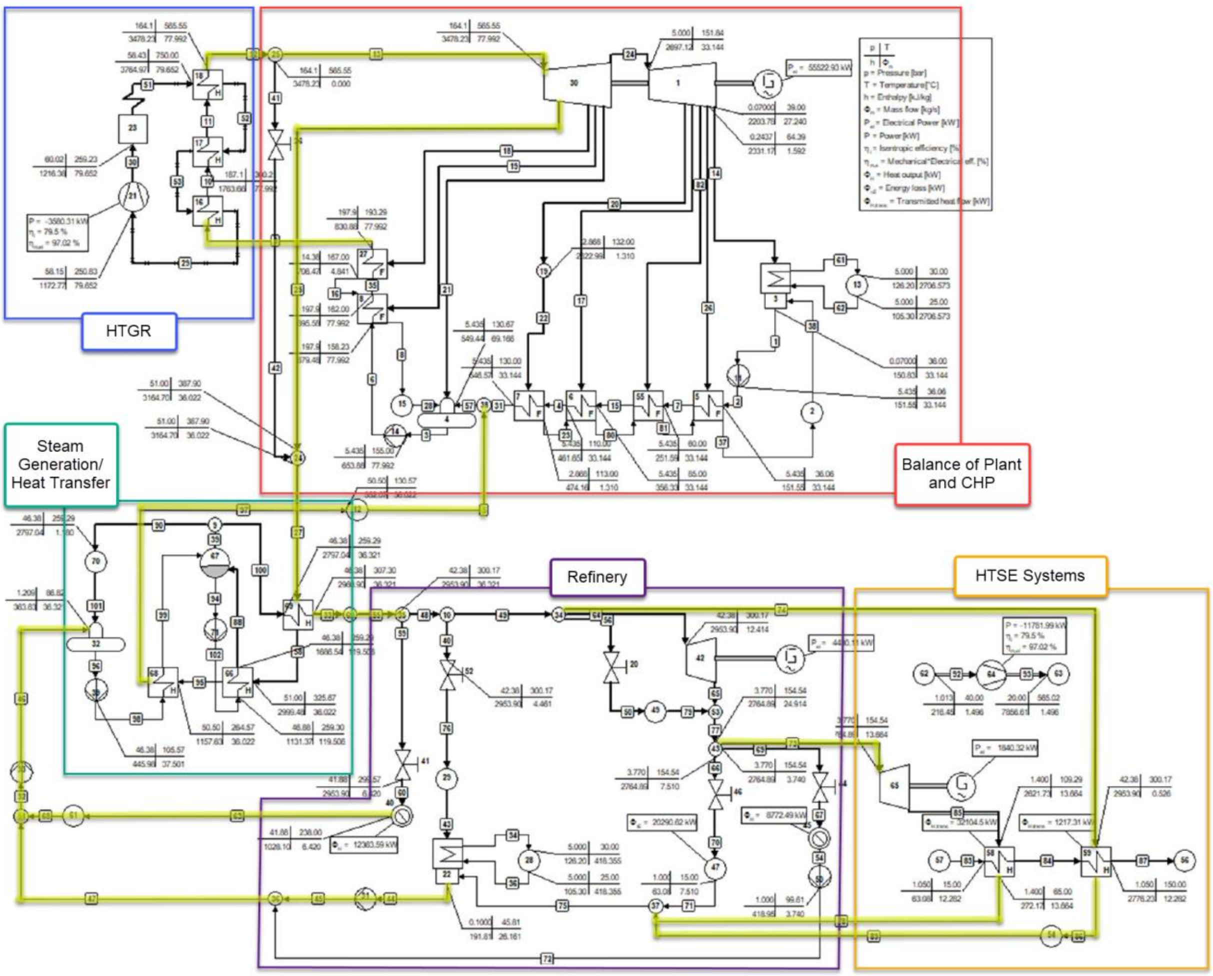


Figure 4-1. Process flow diagram of an HTGR CHP system providing power and process steam to a refinery and steam for an HTEF with main connection points highlighted [12].

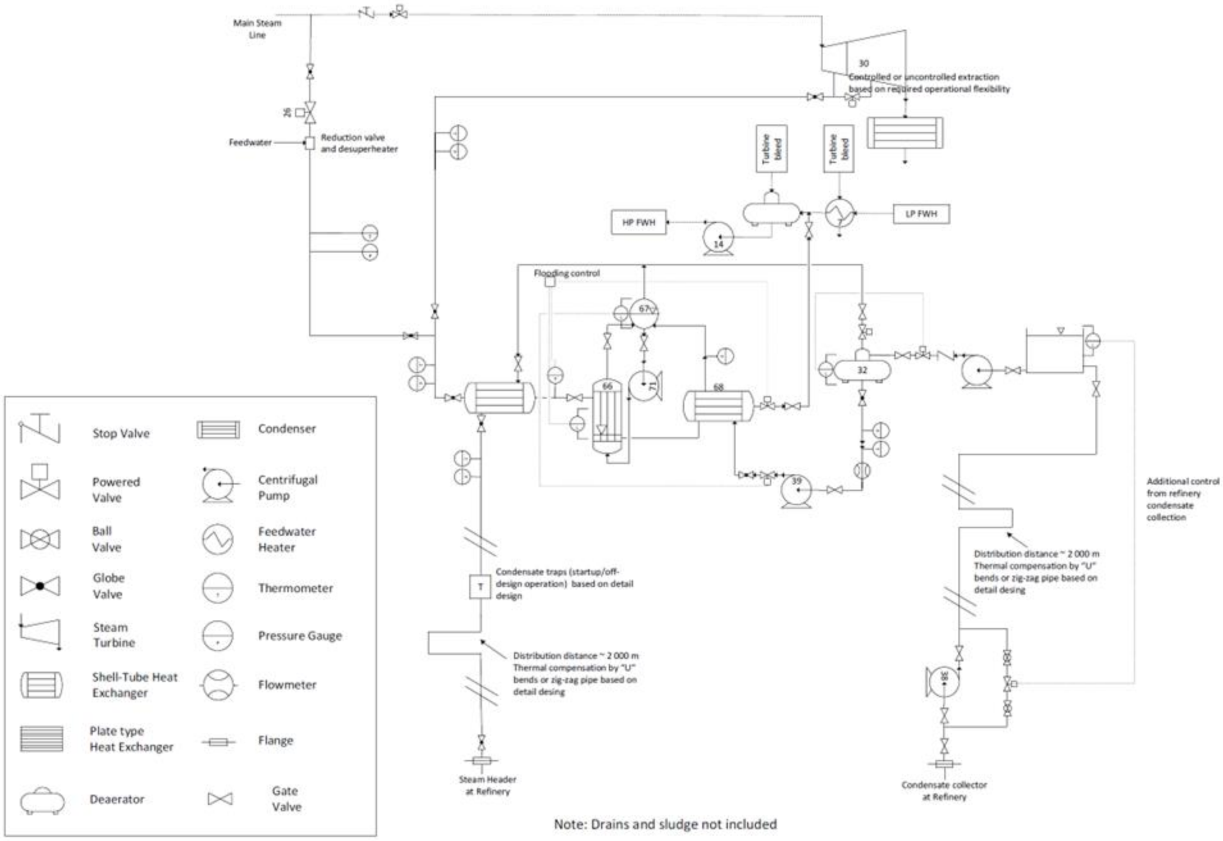


Figure 4-2. P&ID of the heat extraction system coupling an HTGR and refinery [12].

This is an example configuration for heat extraction from an HTGR and can be built upon to define specific component parameters as required for PRA modeling. These parameters inform the changes that affect the safety of the HTGR. Parameters would include pipe dimensions (diameters and lengths), valves and their placement, and operating conditions (e.g., flow rates, temperatures, pressures).

4.2 Direct Electrical Connection

Electric power transfer from the ANPP to the industrial customer is not defined in any previous work where an HES was defined. One option posed in [12] is behind-the-grid coupling which could include direct connection with the ANPP generator. A design by Sargent & Lundy (S&L) [6] looks at a direct electrical connection with an LWR NPP generator to an HTEF. This design is detailed below as an option for electrical power transfer.

The example provided here is behind the meter that taps from the generator step-up (GSU) transformer. This example is one of several options. For instance, a plant specific evaluation may establish that a connection to a unit GSU transformer may not be feasible and or a multi-unit site may need to power a centrally located facility (e.g., one HTEF facility at a two-unit plant) necessitating a connection to the plant switchyard. While this GSU example provides a roadmap for evaluating these types of modifications, this again is an area where the plant specific analysis will dictate the configuration.

Figure 4-4 and Figure 4-5 show the electrical connection to the industrial customer is assumed to run from a tap just outside of the ANPP main GSU transformer to the switchgear at the industrial customer.

The transmission line distance is determined by the safe standoff distance from the hazards analysis, high-voltage (typically 345 – 525 kV) line with protection at each end, a circuit breaker with manual disconnect switches on each side, and primary and backup relays. The first circuit breaker downstream of the tap point also electrically separates the transmission from the ANPP switchyard breaker alignment. As stated in Section 4.3.5 of Reference [6], "The new H2 power line has no effect on the switchyard voltage, breaker alignment, generator automatic voltage generator loading, or the status of offsite power voltage regulating devices." This eliminates the impact of the transmission line on ANPP safety systems that rely on offsite power.

A three winding step-down transformer steps the line voltage down to the 13.8-kV medium voltage required at the switchgear for the industrial customer. The switchgear at the industrial customer is interpreted as drawn, with a circuit breaker-protected bus with four inputs on each winding. The transformers and generator circuit breaker (GCB) also have primary and backup relays. Control panels and power for the relays before the transmission line are within the ANPP switchyard. Then there is a transmission line run over the determined safe separation distance to the industrial customer (Figure 4-5), where protective circuits receive the power from the ANPP. Should these protections fail in an overcurrent event due to loads at the medium voltage switchgear or either of the transformers, the resulting overcurrent at the generator could cause a turbine upset transient event at the ANPP. This failure model is detailed in Section 6.1 of Reference [11].

Alternatively, if the line were to experience a faulted trip, simulations conducted in Section 4.1.3.8. of [6] show that a fault on the three-phase line must be cleared within 0.2 seconds or else it would destabilize the generator and cause a transient at the ANPP. The designed load of the electrolysis process and total electrical demand of the entire HTEF are detailed in Table 4-1. The loads detailed for the 1000 MW_{nom} HTEF are assumed to be a linear scaling (double) of the 500 MW_{nom} HTEF since we assume that the 1000 MW_{nom} HTEF is two adjacent 500 MW_{nom} HTEFs as detailed in Section 3.

Apparent power (S), colloquially known as the total electrical demand that needs to be delivered from the power plant, is the complex sum of real power (P) and reactive power (Q) [13]. This relationship is illustrated by the power triangle diagram shown in Figure 4-3, where S [VA] = P [W] + jQ [VAr]. P is the power that the industrial facility needs to perform its function, while Q is the power required to overcome the net reactance from power cables and transformers in the behind-the-meter AC transmission line.

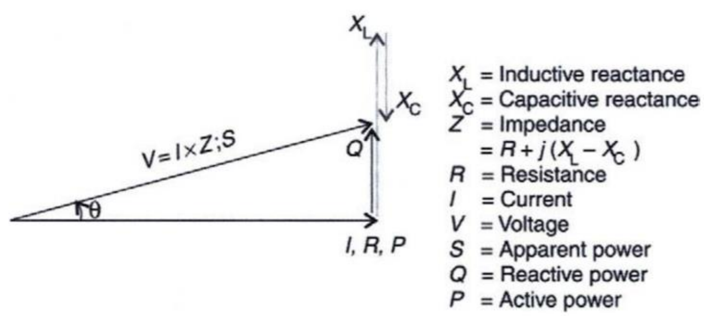


Figure 4-3. Power triangle diagram [13]

The existence of reactance within the network leads to a phase shift between the voltage and current phasors at the load, with a phase angle denoted by theta (θ). Here, the voltage phasor serves as the reference point, and the current phasor is described as "lagging" when considering a counterclockwise rotation of the phase. The power factor (PF) is represented by the cosine of this phase angle (cos θ), and in conjunction with Figure 4-3, is therefore formulated by Equation (1). A theoretical ideal of the power factor is 1 (i.e., no phase angle due to no network reactance). In reality, the power factor may be around 0.9. The longer the cables and the more transformers are in the transmission line, the higher inductive reactance (X_L) is, and the power factor decreases. It physically means that there are more electrical losses.

However, the power factor can be improved by adding capacitance to an inductive network to increase capacitive reactance (X_C) in what is known as power factor correction.

$$PF = \cos\phi = \frac{P}{\sqrt{3} \times V \times I} = \frac{P}{S} \quad (1)$$

The 100 MW_{nom} HTEF requires 105 MWe active power to perform electrolysis. An additional 10% active power is assumed for plant auxiliaries and ancillary loads, with another 10% margin to account for fluctuations. The resulting active power (P) becomes 120% of 105 MWe which is 126 MWe. The power factor (PF) of the transmission line was designed to be 0.92 (i.e., a phase angle of 23°) by utilizing capacitor banks to provide power factor correction and to compensate for transformer reactive power losses (Q) [6]. Therefore, the apparent power (S) for the 100 MW_{nom} HTEF comes down to 126/0.92≈140 MVA. Similar assumptions were applied to the 500 MW_{nom} HTEF, excluding the 10% active power margin since minor fluctuations are non-issues in such a high active power rating, to come to the apparent power rating (S) of 550/0.92≈600 MVA. Since the 1,000 MW_{nom} HTEF is a dual 500 MW_{nom} HTEFs, its apparent power is 1,200 MVA. By applying the same set of assumptions to other industrial facilities, their apparent power is between 30 to 40 MVA. These values are listed in Table 4-1.

Table 4-1. Electrical demand of reference industrial customers.

Reference Industrial Customer	**Electrical Load (Active Power) [MW_e]**	**Total Electrical Demand (Apparent Power) [MVA]**
Hydrogen HTEF [1]	100	140
	500	600
	1,000	1,200
Synthetic Fuel Plant [7]	26	35
Wood Pulp & Paper Mill [2]	25	35
Petroleum Refinery [2]	28	40

Considering these industrial customer design features and most recent data, no additional over-current protection is recommended.

Overcurrent Protection Beyond the Reference Industrial Customers: If the ANPP is tasked to provide larger behind the meter loads, for instance a direct connection to a data center, it may be advisable to seek out further overcurrent protection. Initial research was performed in this area. First, a dump load or battery energy storage system (BESS) was considered for load shedding. Current literature on dump loads and BESSs shows applications for microgrids, renewable energy, and other systems that are smaller in electrical demand by an order of magnitude or greater [14]. Unfortunately, there is no indication that there is history or consideration of such protection even for the MV/MW level systems such as the HTEFs considered in Reference [11]. Feedback from subject matter experts (SMEs) and industry also support this observation [15]. HTEF SMEs at INL have explained that there are very few SOEC systems at industrial scale worldwide (the few being in Europe), so it is difficult to determine the nature of any overcurrent situations, and the protections required at that scale. Industry and other renewable energy SMEs have so far only referenced smaller magnitude power demand systems or have not indicated wide discussion or concern for dump load, BESS, or other load shedding protections for MV/MW level systems.

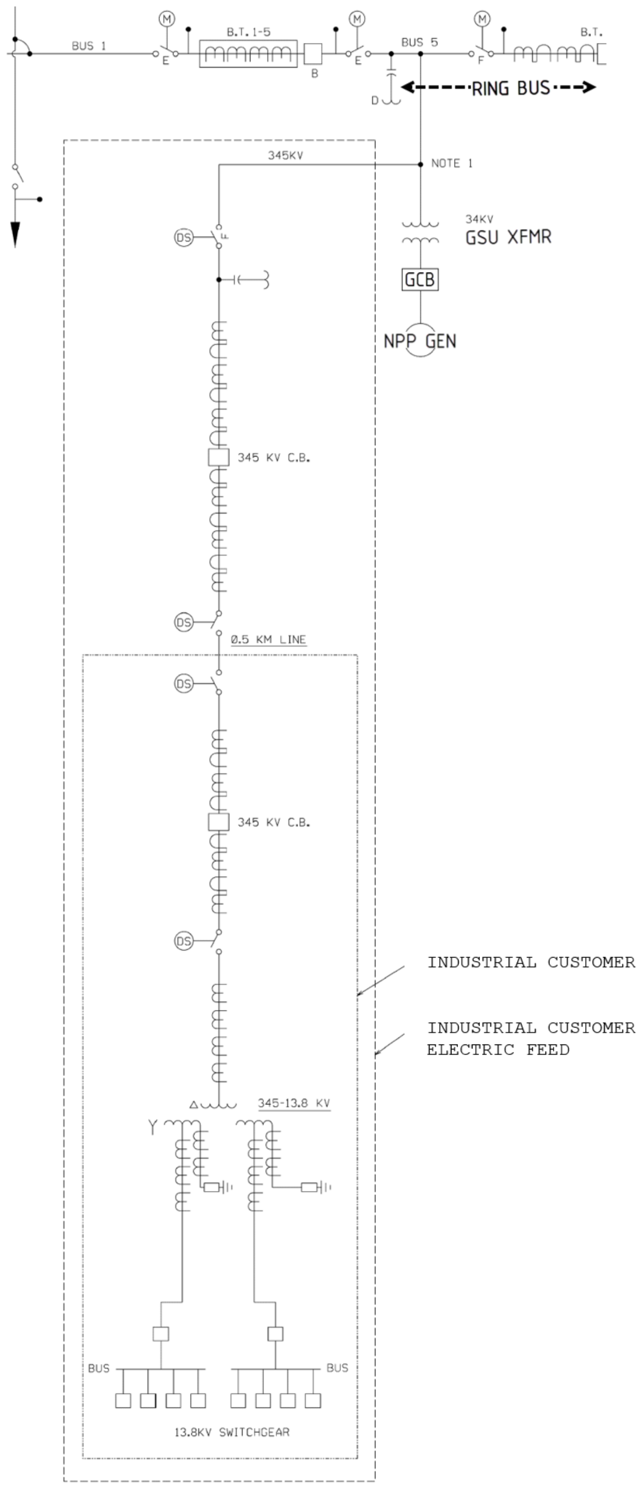


Figure 4-4. Transmission line and portion of ring bus switchyard arrangement at ANPP [6].

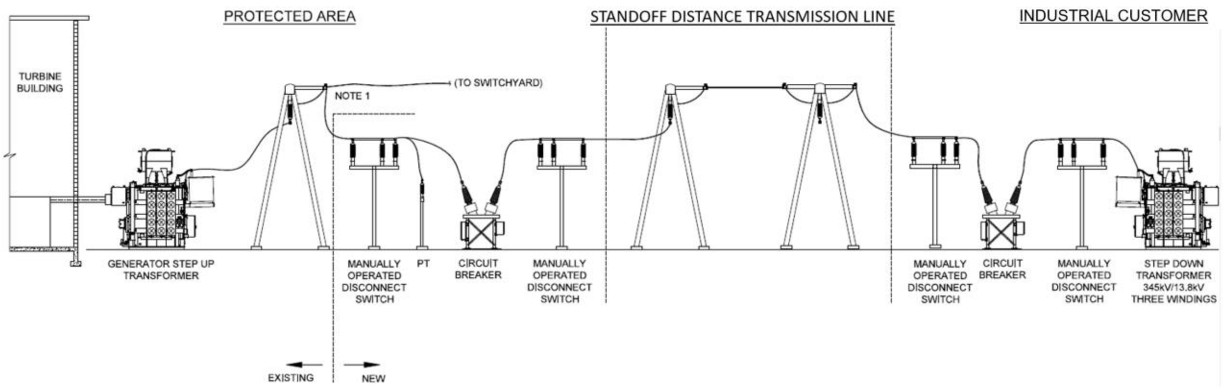


Figure 4-5. Behind-the-meter physical layout of electrical feeder [6].

5. HAZARDS ANALYSIS OF A NUCLEAR POWER PLANT SUPPLYING ENERGY TO AN INDUSTRIAL FACILITY

The hazards associated with co-locating an industrial process next to an ANPP were researched through accidentology studies of historical industrial accident databases, identification of products and feedstocks and their properties, and through interviews and FMEA input from SMEs, utility engineers, S&L architectural engineers, and hydrogen experts at Sandia National Laboratories (SNL). Proposed design drawings and options of the conceptual HES were reviewed and evaluated in a system-level FMEA.

5.1 Accidentology

Industrial accidents are reported and recorded by safety agencies around the world. The study of trends and frequency of these accidents is called accidentology. Accidentology identifies what has happened at these facilities. This is beneficial in determining accident frequencies and consequences. The hazards identification and consequence quantification process continue with assessing the properties of the hazards, regardless of whether the hazard has manifested into an accident at the industrial site. We reviewed databases from the U.S. and internationally for each type of industrial customer considered in this report.

5.1.1 Hydrogen Electrolysis

We have included the hydrogen electrolysis accidentology even though hydrogen electrolysis is not one of the direct reference industrial customer facilities studied for this report. The reason is that production and use of hydrogen is required for all the reference facilities.

Worldwide incidents involving hydrogen are reported in the hydrogen incident and accident database (HIAD) maintained by the European Commission [16]. As of February 11, 2024, there are 755 events recorded in the database, 162 of which happened in the United States. The statistics of all incidents are shown in Figure 5-1. The top three causes of these incidents are management factors, material/manufacturing error, and human factors. Wen et.al. explained these factors as follows [17].

- Management factors: poor management planning causing overstressed workforce; failure to learn from previous incidents; lack of clear definition of responsibilities; poor management of health and safety, etc.
- Human factors: low competency levels; fatigue; disheartened staffs; medical problems, etc.
- Material/manufacturing error: Components malfunction due to material failures or manufacturing errors.

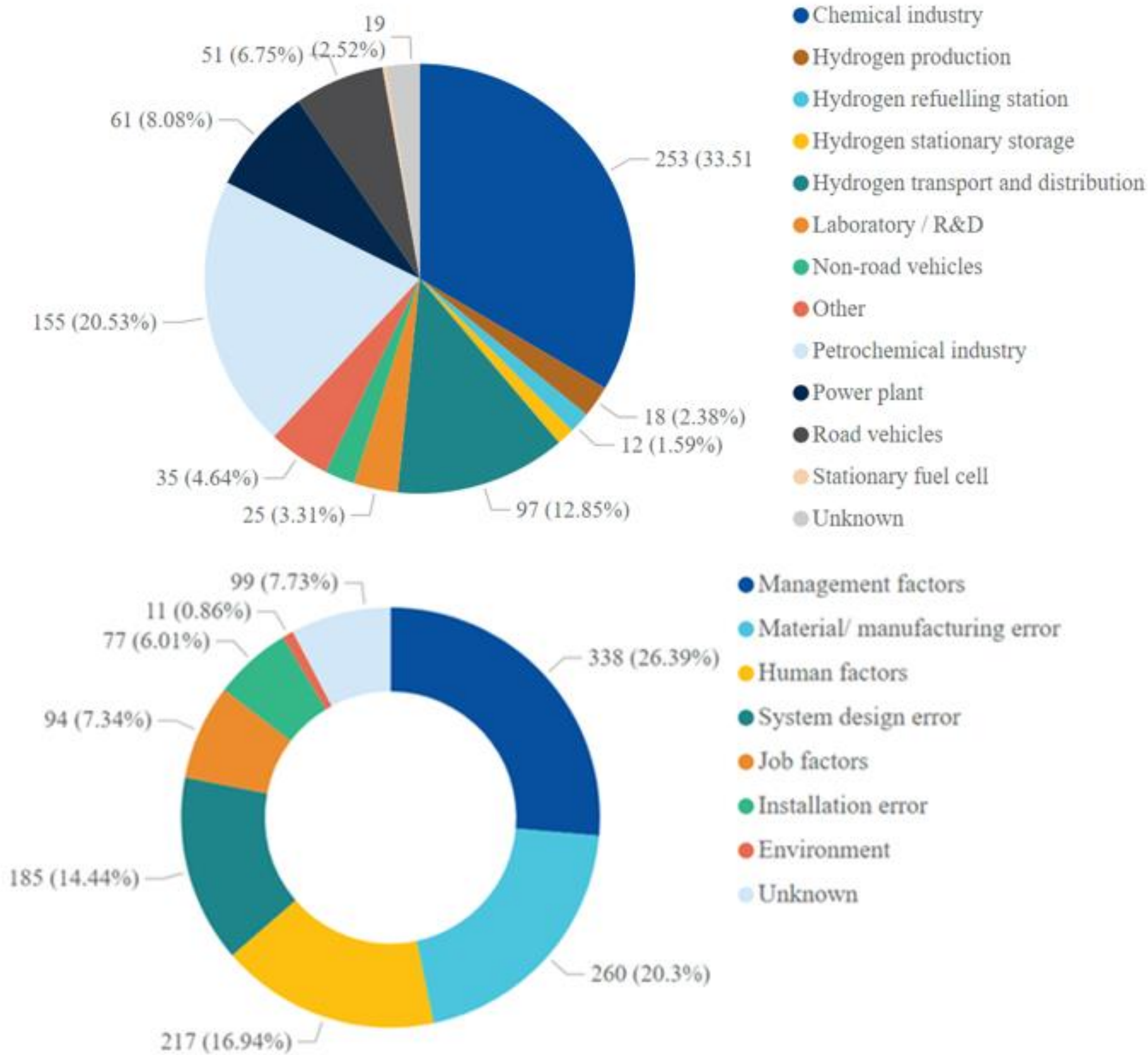


Figure 5-1. Hydrogen incident statistics per application type (top) and their causes (bottom) [16].

The “soft factors” include management factors, human factors, and job factors, which contribute to half of the incidents. Wen et al. highlighted that most of the incidents under this category were caused by a lack of regular/appropriate maintenance and inspection, and lack of attention for safety devices during maintenance and inspections such as fittings, gaskets, flanges, and valves. Lack of adequate staff training exacerbates these issues. Management factors contribute to these incidents through the lack of safety supervision during certain repair work, lack of adequate procedures, and lack of clear guidance about lifetime of critical components. These areas can be improved through regulations and establishing a good safety culture. Meanwhile, for the technical aspects, hydrogen gas itself easily dissipates into the atmosphere when leaked because it is lighter than air. Therefore, a hydrogen cloud detonation event creating a large overpressure is unlikely if confinement safety protocols are followed as prescribed by the National Fire Protection Association (NFPA) standard NFPA-2 [18].

Approximately 74% of the hydrogen incidents caused fire and/or detonations. The incident consequences per specific application supply chain stage are plotted in Figure 5-2. As the figure shows, about 30% of accidents happened when hydrogen was used as a process gas, mostly in the petrochemical industry. For example, two separate accidents occurred in 2022 that involved fire due to hydrogen leakage from a hydrogen compressor of a reforming unit at a refinery. In both cases, the hydrogen emergency flow cut-off was activated to stop the hydrogen leak, and a protective combustion was carried out following the safety protocol to decompress the unit.

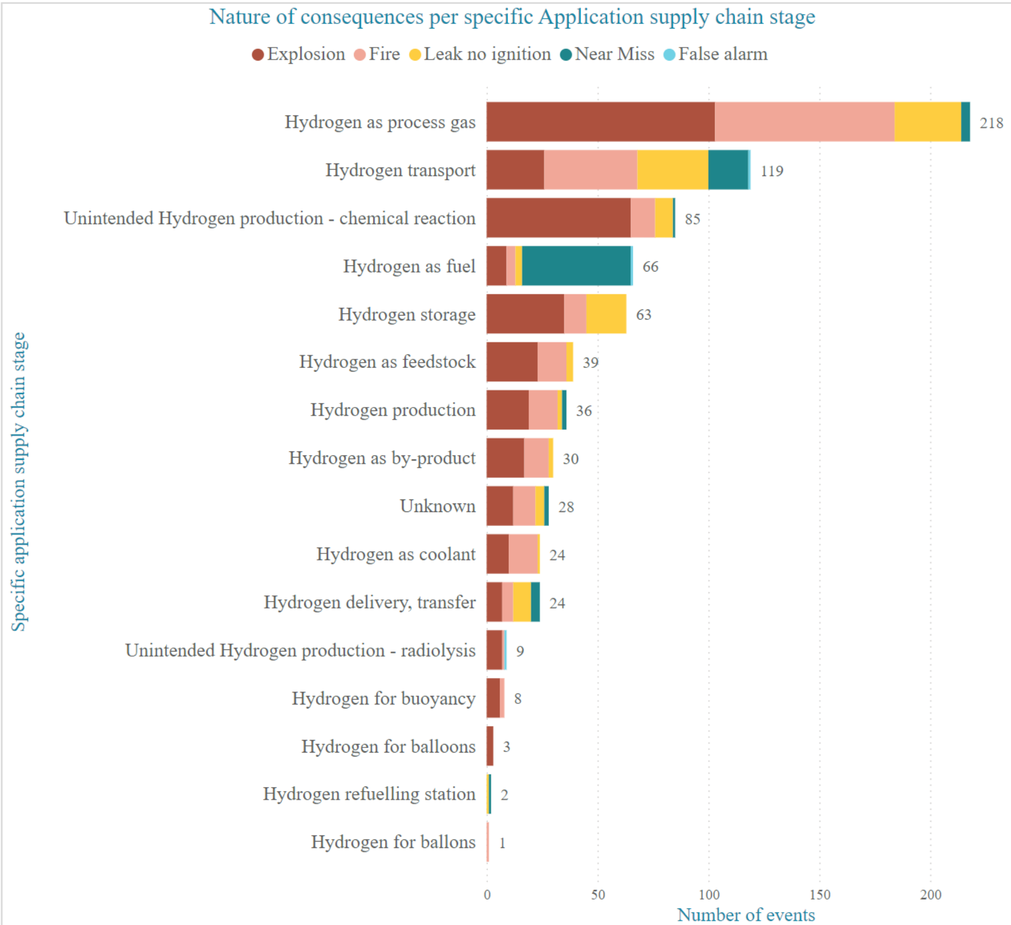


Figure 5-2. Hydrogen incident consequences per specific application supply chain stage [16].

Of all the recorded incidents, about 5% of cases happened during the hydrogen production process. The causes of these incidents are plotted in Figure 5-3. The top causes are similar to the overall recorded causes in Figure 5-1, except those contributions from human factors decreased and they are replaced by contributions from system design errors. This is because hydrogen production is less dependent on human actions compared to other activities (e.g., hydrogen transport and hydrogen refueling). An example of system design error is the explosion of three hydrogen buffer tanks at an experimental facility in South Korea in 2019. These tanks were receiving hydrogen produced from electrolyzers powered by solar panels. An investigation revealed the root cause was a static spark that ignited oxygen levels above 6% in the hydrogen tank, which is the minimum for an explosion. This unacceptable oxygen level was caused by the electrolyzer being run below its required power level. This minimum power level was required to operate the asbestos separation membrane, which drew in half of the electrical power supplied. Unfortunately, the electrolyzer often received subpar power because the solar panels' output fluctuated with sunlight exposure. A contributing cause was that the system lacked oxygen removal devices and anti-static systems.

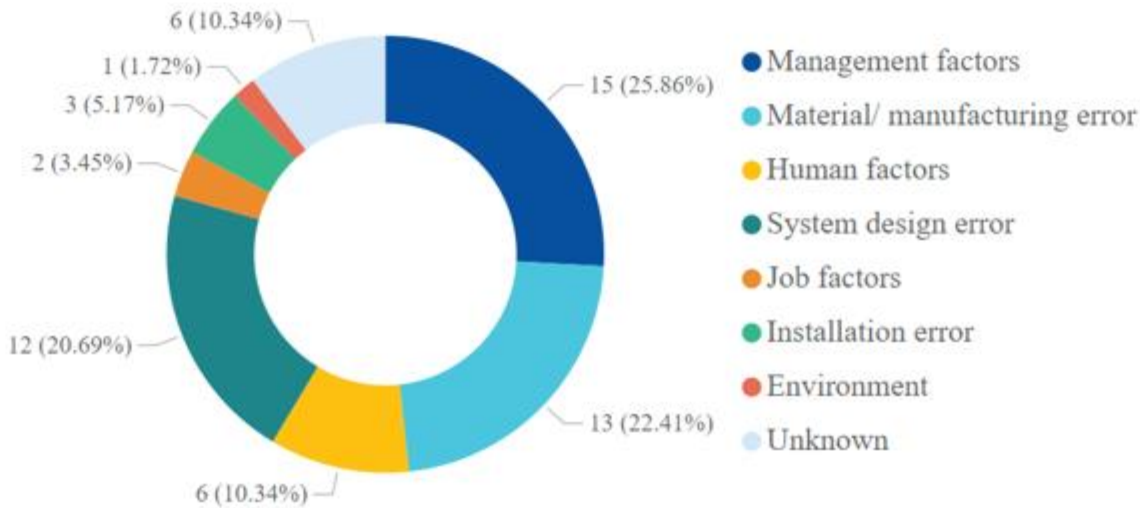


Figure 5-3. Accident causes during hydrogen production [16].

5.1.2 Methanol Plant Accidentology

Methanol accidentology overall shows that many accidents occur because of lack of inspection. When operators are unaware of the concentration or presence of methanol in the system or environment, adding heat to the system or environment can result in a rapid change in conditions. The consequences of known accidents have resulted in equipment rupture and burning, death, and injury.

The overall frequency of methanol-related accidents includes a variety of situations. The U.S. Department of Labor Occupational Safety and Health Administration (OSHA) records 26 accidents related to methanol, with 12 accidents resulting in fatalities [19]. From the Analysis, Research, and Information on Accidents (ARIA) database [20], there were 149 records of accidents related to methanol. A record of an accident in the ARIA database highlights that there can be multiple ignition sources. To remove palladium residue from a chemical reactor, technicians cleaned it with boiling methanol. After cleaning, the opening of the reactor was not immediately closed. During this time, the residual methanol vapors from the opening were ignited. The most likely cause reported was from a palladium, methanol, and oxygen reaction or, less likely, but still possibly, from an electrostatic discharge from a nearby document console. Although palladium is not a catalyst material used in methanol synthesis from syngas, it is important to note that mixtures of methanol with other streams may increase likelihood of ignition.

In the U.S. Chemical Safety and Hazard Investigation Board (CSB) database, there is less direct searchability and accounting for methanol related accidents [21]. No direct results were found for the synthesis of methanol from syngas. Some results were found where methanol was used in other synthesis reactions, used as a cleaner for other chemical plants, or used in a mixture for other chemical reactions. The CSB notably reported on an investigation of the Bethune Point Wastewater Treatment Plant accident and a summary of other flammable gas accidents. The wastewater treatment plant had a continuous feed of methanol and a 10,000-gallon storage tank. As an operator was using a cutting torch to remove the metal roof directly above the methanol tank, vapors coming from the tank vent were accidentally ignited. This also led to the flame flashing back into the storage tank that resulted in an explosion inside the tank that created multiple methanol piping failures and a large fire that engulfed the tank and workers. Two workers died and another was severely burned. The results of the investigation reported that the cause of this accident was due to a lack of inspection and maintenance of the flame arrestor. The vent through the flame arrestor was constantly open and therefore always discharging methanol vapors due to the corrosion of the arrestor by the methanol. In this degraded state, it did not prevent fire outside of the tank from igniting the tank's contents. The CSB also published a lesson learned on preventing deaths during hot work in and around flammable gas tanks based on explosion and fire accidents similar to the one at the Bethune Point Wastewater Treatment Plant [22]. The lesson they listed as the most important was to analyze the hazards and to monitor for combustible gas as a sign of a potentially flammable atmosphere.

5.1.3 Syngas Production Accidentology

Currently, there is no history of accidents involving syngas. Stolecka and Rusin [8] analyzed possible hazards related to syngas by developing an ET to track various consequences following damage to a syngas pipeline. The probabilistic consequences are shown on the left-hand side of Figure 5-4. The most likely consequence is that syngas is dispersed without ignition. This is because the flammable elements are diluted with non-flammables such as CO_2 and H_2O, thereby increasing the mixture's lower flammability limit and flash point. They also analyzed the radius of consequences for a reference coal and biomass plant. The maximum distances of those consequences are shown on the right-hand side of Figure 5-4. For that reference plant, the safe distance perimeter may be set against the jet fire hazard of 126 meters, which also accommodates explosive and toxicity risks.

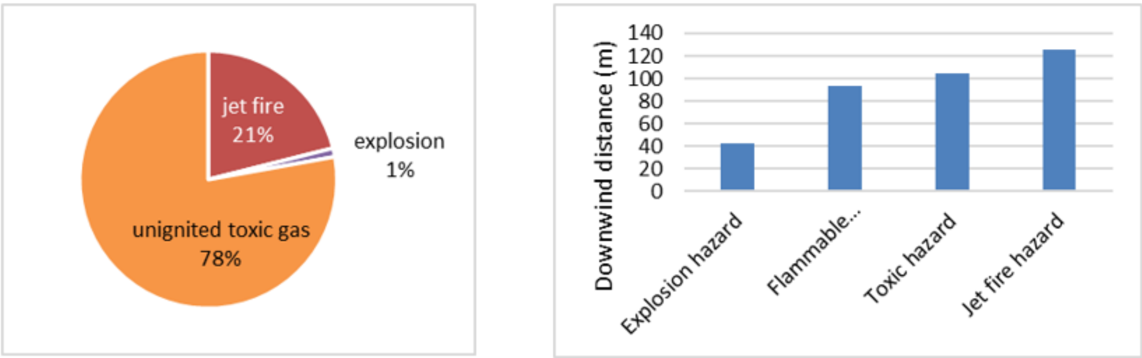


Figure 5-4. Probabilistic consequences of syngas release.

5.1.4 Oil Refinery Accidentology

The statistics from OSHA of 165 accidents in oil refineries from 1984 to 2024 are shown in Figure 5-5, 58 of which caused fatalities [19]. Among them, the Texas city disaster was believed to be the most catastrophic refinery accident in history, killing a total of 581 people including dockworkers [19] [20], residents, and sailors, and more than 5,000 people were injured. More than 150 miles of the areas from the ignition points were impacted. The root cause of this accident is still unknown, but a welder's torch was suspected to be the source of the ignition point. The Texas city disaster and three other events resulted in changes to the regulations. The root causes of the fires and explosions documented for these events were the release of flammable chemicals due to (1) rupture of the pipe or tank, (2) inadequate training of the workers, and (3) improper installation of the equipment. Pipe or tank rupture can result from the long-term degradation of the materials from the corrosive liquids such as hydrogen sulfide or the shock rupture due to an overpressure event in the systems. While the degradation effects on the piping or tank can be detected and repaired during the maintenance period, the shock rupture would be challenging to predict even if a pressure-monitoring system is installed. Safety features should be improved to mitigate the potential fires if those pipes or tanks containing flammable liquid or gas fail. For inadequate training and installations, a more rigorous preventive maintenance and scheduled training are required to prevent accidents.

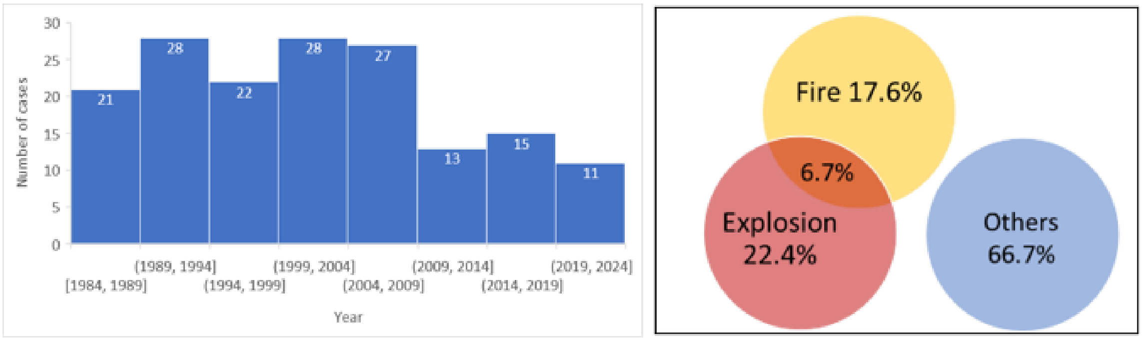


Figure 5-5. Historical statistics of accidents in oil refineries: over time (left) and consequences (right).

As for the cause of accidents, detailed refinery accidents reported by the CSB [21] show that most accidents are caused by the confinement of vapors, piping and heat exchanger failures, and inadequate procedures or human actions. There were two accidents associated with the confinement of vapors that happened when a buildup of flammable vapors ignited with an ignition source. For example, an overflowed flammable vapor cloud flowing down to the ground ignited with an idling diesel pickup truck present during the start-up of a raffinate splitter tower at the BP Texas City Refinery in 2005 [23].

Most accidents related to refineries in the U.S. CSB database were caused by piping and heat exchanger failures, and inadequate procedures and human actions. There were six accidents associated with piping and heat exchanger failures where the flammable liquid leaking from the failed structure ignited or exploded based on the pressure conditions. Piping and heat exchanger failures can be prevented by a preventive maintenance program and can help detect the precursor (e.g., crack initiation and crack propagation) of the accidents. Methodologies for piping reliability analysis that considered the underlying failure mechanisms and maintenance activities were reviewed in [24].

Meanwhile, there were six accidents associated with inadequate procedures or human actions. In this type of accident, workers failed to operate a critical system or component because they inadequately followed the operation procedure or there was miscommunication between the workers that led to a catastrophic consequence. Inadequate procedures and human actions can be mitigated by regular training and licensing requirements for the operators and updating operating procedures to provide more clarity and guidance.

To prevent fire due to high flammability of feedstocks and products, fire protection programs should be enhanced and tested in refinery plants. The impacts of an overpressure event can be mitigated by adjusting the distances between the industrial applications and ANPPs [1]. However, longer distances between a refinery plant and the ANPP will increase the cost of thermal delivery systems due to the cost of piping material and energy lost during transport. INL is performing ongoing research to optimize the heat delivery and transportation costs between the ANPPs and industrial applications [12].

5.1.5 Pulp and Paper Mill Accidentology

Common accidents for the pulp and paper industry include chemical exposure and burns, fires, explosions, water contamination, and mechanical accidents, (e.g., falls or hands/fingers caught in machinery). The ARIA database yielded ample results, including nine accidents uncovered when searching “pulp mill,” and 36 when searching “paper mill” [20]. Only one accident extended outside the mill perimeter. Accidents listed in the OSHA database on pulp and paper mills are largely mechanical accidents pertaining to operating equipment and the handling or moving of product [19]. Pulp and paper mill accidentology revealed many common accidents stemming from various causes. Accidents listed in the CSB database included a significant explosion and an incident of H_2S toxicity, both of which involved fatalities, though neither extended beyond the mill boundary [21].

Based on accidentology studies of pulp and paper mill accidents, the lessons learned about the causes of accidents include:

- Mechanical accidents are numerous. Following good procedures is necessary.
- Many unwanted chemical reactions are possible. Toxic vapor clouds and toxic smoke plumes are valid concerns. The impacts of such accidents can potentially extend outside the mill; however, no accident of this nature has occurred to date.
- Product spillage within the pulp and paper mill reached adjacent waterways, causing contamination and pollution that could affect an ANPP's water intake (if the design requires one).

The consequences of pulp and paper mill accidents are often limited to a single employee being hurt by one of the mechanical or chemical processes in the mill. Farther-reaching consequences, still confined to the mill, stem from hot work conducted around flammable and explosive chemical tanks, a common occurrence across all three primary industrial processes examined for this report. In all such accidents, toxicity from inadvertent chemical reactions is a concern locally to the mill. Some accidents occurred as a result of products that spilled into adjacent rivers. One rupture of a black liquor tank caused contamination that extended outside the mill. Black liquor is a highly alkaline manufacturing residue of organic matter, NaOH (caustic soda), and other chemical products that serve as boiler fuel in the paper pulp production process.

Based on accidentology studies of pulp and paper mill accidents, the lessons learned about consequences include:

- Most accidents affected only the pulp and paper mill, its workers and contractors, and the emergency responders.
- Pulp and paper mill accidents can affect the ANPP's water intake (if the design requires one).
  - The black liquor tank rupture accident demonstrated the potential for environmental and health effects extending beyond the pulp and paper mill, including raising the pH of the river to the point that a co-located ANPP using this river for intake would be forced to shut down to protect its equipment.
  - Another accident spilled "broken pulp" into the river for 13 km. These solids may cause intake screen blockage at the ANPP.

5.2 Design Options and Assumptions

The HES and HTEF design options and assumptions considered for the representative ANPP, HES, and HTEF are listed in Table 5-1. Assumptions are made based on physical properties and a generic geographic region.

Table 5-1. Industrial facilities design options and assumptions.

Component/Parameter	**Options**	**Assumptions**
Electrical power linkage from ANPP to industrial facility	Direct linkage, load following or connection to the grid then to the industrial facility	The ANPP is connected directly to the industrial facility in a behind the meter fashion.
Loss-of-offsite-power (LOOP) frequency		Default LOOP frequency is site based.

Component/Parameter	Options	Assumptions
Multiple detonations at industrial facility		Bounding accident is assumed for the first detonation overpressure. Ensuing detonations will not exceed bounding accident but may cause the bounding accident. ANPP SSCs will not be adversely affected by prior non-bounding detonation overpressure events.
Blast shielding or other engineered barriers at the industrial customer other than the combined production header		Default analysis is performed without shielding.

5.3 Failure Modes and Effects Analysis

Proposed facility sizes and operations were reviewed and evaluated in a system-level FMEA for each industrial facility covered in this report. The system-level analysis does not attempt to assess the operations down to a component level. The objective is to identify hazards and their consequences. The FMEAs were performed for four perspectives. The main focus is on #1 below: NPP safety of the general public. This is the only FMEA that is used to identify the hazards that cause initiating events at the NPP. The other three FMEAs are provided for general use in determining non-radiological safety or economic impacts.

1. Nuclear power plant safety of the general public
    a. This is the most important aspect of this report for licensing considerations
2. Industrial facility safety
    a. Important for the industrial facility operators and nearby public
3. Public perception
    a. This is important for continued operation of the two facilities and can extend beyond actual safety concerns
4. Economic impacts
    a. Loss of the industrial customer or loss of the NPP energy supply adversely affect the nearby facilities.

The safety of the NPP is the focus of this report and feeds into the safety analysis decisions both for deterministic analyses to decide what hazards need to be quantified, and for probabilistic analyses to decide where the hazards fit within the PRA. The other three perspectives are provided in tabular form for the reader's information.

Each potential failure event/mode evaluated among all four perspectives were ranked with respect to severity of the event to the perspective focus, frequency of the event, and detection of the event. Each of these three categories were ranked on a scale of 1–10 then were multiplied linearly to determine a risk priority number (RPN) in which lower values indicated less risk and higher values indicated greater risk. There is no RPN cut-off at which the hazard will not be modeled in the PRA. One of the uses of the RPN scores was to identify which hazards were of most importance to eliminate through safe facility separation distance considerations. See Equation (2).

$$RPN = S \times F \times D \quad (2)$$

where S is the score for severity, F is the score for frequency, and D is the score for detection, all of which are integer values.

As much as possible, the scaling of each category was defined to minimize variability in scoring. This is detailed in Table C-1.

The flammable and detonable products and feedstocks for methanol, syngas, refinery, and pulp and paper are listed in Appendix F. The chemical properties of flash points, auto-ignition temperature and flammability limits for chemicals found in methanol, syngas, refinery, and pulp and paper mill are summarized from [2].

The toxic products and feedstocks for methanol, syngas, refinery, and pulp and paper are listed in Appendix G. The time-weighted average (TWA), short-term exposure limit (STEL), oral and dermal toxicity levels for methanol, syngas, refinery and pulp and papers are summarized from [2]. Based on the definition from OSHA [25], TWA refers to "the employee's average airborne exposure in any 8-hour work shift of a 40-hour work week which shall not be exceeded." STEL is defined as "the average exposure to a contaminant to which a worker may be exposed during a short time period (typically 15 – 30 minutes)" [26]. Most of the oral and dermal toxicity in the tables using acute toxicity estimate (ATE) as a measure to define the toxicity level. This is used to define the categories of each of the toxic materials [27].

5.3.1 Nuclear Power Plant Hazards Analysis

A group of SMEs were gathered for an FMEA to determine the hazards presented to the ANPP that are not unique to the external hazards of the reference industrial facilities. All hazards were considered since there is a wide variety of ANPP design requirements and features (e.g., LOOP, condition of water intakes). The results of this FMEA informed the reference facility FMEAs discussed starting in Section 5.3.2.

The FMEAs performed for this report were all done at a high level. The intent was not to design or improve upon the generic proposed designs. The intent was to stay at a system level and concentrate on safety first above reliability and resilience.

An outline of the topics considered for the FMEA include:

- External overpressure event effects on ANPP
- Industrial customer specification recommendations and assumptions for safety
  - List of industrial customers under consideration
- Thermal and electrical load effects on ANPP
  - Thermal and electrical load power profiles supplied by the ANPP to the industrial customer
- Hot standby mode
- Placement of the HES reboilers
- Production chemical routing options and effects on risk
  - Chemical storage risks
- A list of heat-transfer fluids (HTFs) under consideration and their properties.

Possible external overpressure event effects on the ANPP were summarized to include the damage to the containment, damage to external coolant storage tanks, damage to switchyard components causing

LOOP, damage to above-water spray mechanisms in spray ponds, debris in spray pond or cooling tower pond, and service water pump house damage.

Note that blast overpressure-borne missiles were not assessed in this report and must be considered on a site specific basis.

Possible thermal and electrical load effects on the NPP were summarized as a load drop feeding back negative reactivity into the ANPP, possibly causing a reactor trip.

The secondary or tertiary heat exchange components were considered for placement within the turbine building or in a building separate from the turbine building that would be designed and fabricated to the same requirements of the turbine building. The benefit of placement in the turbine building (if room in the existing NPP is available) is lower costs. The benefit of having its own structure is increased safety, as the FMEA results in the appendices identify. A few ANPP manufacturers have designed separated thermal storage and delivery facilities that would be regulated for safety should they be built within the OCA.

Industrial process production and storage were discussed as potential hazards.

5.3.1.1 List of Nuclear Power Plant Hazards Identified

The NPP-specific FMEA results are used in all the industrial facility FMEAs. All risks identified are evaluated in the sections that follow. Those not screened by an engineering evaluation are mapped into the respective ETs, and the IE frequency for these ETs are re-quantified for the respective BWR and PWR models based on the increased frequency of occurrence caused by the addition of the HES and the industrial customer at a calculated safe distance from critical SSCs.

The hazards either affected or added to the PRA by the addition of the HES and the industrial customer are listed in Table 5-2. Also listed in the table is the ET to which the hazard would map to and the status ("Included" or "Screened" from the PRA) from the FMEA panel. Potential hazards considered in adding the HES and locating the industrial customer at a calculated safe distance include a detonation at the industrial customer causing an overpressure event at the NPP site, an unisolable steam pipe leak in the HES outside of the ANPP main operating fluid isolation valves, a heat exchanger leak in the HES either causing an unisolable thermal operating fluid leak or contaminating the customer industrial customer thermal loop, and the prompt loss of customer thermal load to the HES.

Table 5-2. FMEA-derived potential failures from hazards and PRA ET assignment.

Hazards	Potential NPP Process Functions Affected	Potential PRA ET Assignment	FMEA Hazard Status
Detonation at industrial customer	Loss of Offsite Power	Switchyard-centered LOOP	Screened through safe separation distance
	Loss of service water (spray pond damage or debris, cooling tower pond debris, service water pump house, forced air cooling)	Loss of Service Water System No generic PWR tree affected	Included Screened unless spray pond is also the ultimate heat sink

Hazards	Potential NPP Process Functions Affected	Potential PRA ET Assignment	FMEA Hazard Status
	Critical structure damage (Reactor containment, condensate storage tanks (CST), or other coolant supply tanks)	XXX-DETONATION[1]	Included, but screened by safe separation distance
HES steam pipe rupture outside of ANPP operating fluid isolation valves	Missile damage in turbine building (if HES located in turbine building)	Main (large) thermal line break in HES TRANSIENT	Included (screened if HES is not in the turbine building)
	Main (large) thermal line rupture (MTLB), unisolable leak	MTLB-HES	Included
HES reboiler leak (Primary to Secondary Side	Large leak/rupture: Main thermal line unisolable leak	MTLB-HES	Included
	Small leak: Contamination of the HTEF heating loop	Not a design basis event. Economic risk.	Screened for PRA. There is an economic and environmental concern
Prompt steam diversion loss, feedback	Each ANPP design needs to be evaluated for this effect	Unknown, design specific	Unknown, design specific
HES steam rupture in the turbine building	Turbine building SSC damage, possible safety bus damage, depending on plant configuration	TRANSIENT, emergency power capability	Screened out by recommendation to not place HES in turbine building
General Plant Transient Due to Overcurrent from Electrical Transmission	Turbine disruption	TRANSIENT	Included, but very low effect for LWRs that were evaluated in [11]

[1] Potential new ET if a probabilistic argument is made where an evaluated overpressure damages critical structures.

5.3.2 Methanol Plant Hazards for use in FMEA

The hazards that can affect the operation of methanol plants are summarized Table 5-3, which highlights the hazards associated with syngas, methanol synthesis, distillation and purification processes. The inherent properties of feedstocks, intermediate streams, and finished fuel products pose severe fire, explosion, chemical exposure, and toxicity hazards. The operating condition of the methanol synthesis process involves high-temperature and pressure hazards.

Table 5-3. Methanol hazard summary.

Process	**Hazards**
Syngas Production	Fire, explosion, high temperature
Methanol Synthesis	Fire, explosion, high temperature, pressure, chemical exposure, toxicity
Distillation/Purification	Fire, chemical exposure, toxicity

From Table 5-3, the hazards include fire, explosions, high temperature, pressure, chemical exposure, and toxicity. The fire and explosions hazards are relatively easy to detect based on the flame and smoke, along with the sounds from the ignition sources as described in the previous section. The temperature and pressure should be monitored in each process, and the monitoring system can report some potentially abnormal events before it becomes an accident. Chemical exposure poses some toxic concern if the undetected toxic chemicals are released to the environment. The toxic chemicals in methanol production include methanol and syngas, which are challenging to detect since they are colorless, and the odor does not have a specific distinction from other products. Leakage of methanol and syngas would lead to fire and explosion due to their high flammability.

Another concern arises when one of the feedstocks (syngas) is released to the environment. The size of the impacted area depends on the composition of the syngas. INL has ongoing research to model the syngas release and potential toxicity level using Areal Locations of Hazardous Atmospheres (ALOHA).

These hazards are analyzed in an FMEA for a nuclear-integrated methanol plant with respect to four perspectives: the ANPP, the methanol facility itself, public safety and perception, and economic impact to the methanol facility. Results of the FMEA can be seen in Appendix D.

The primary mechanism of failure evaluated was methanol detonation at the facility as most recorded accidents are detonations. Methanol fires are difficult to detect visually due to its nearly colorless flame. Also, methanol vapors are slightly denser than air [28] and highly flammable [29] so it should not travel downwind significantly before ignition if released.

If methanol is combusting and generating a fire within an enclosed space, it can mature into a detonation due to build up of pressure. Other possible initiators are runaway reactions or methanation, which can lead to a sudden increase in temperature and pressure.

Although there are many hazards or effects of methanol detonation and other identified mechanisms of failure, many of them can be mitigated by siting the methanol plant at a safe distance from the plant.

Other considerations beyond the methanol reactor itself include the equipment required to process the feedstock in preparation for the reactor such as the RWGS system and the CO2 capture system using selexol solvent. For these chemical processes, the severity of the hazard can vary depending on the process conditions and mechanism of failure. If pressures, concentrations of chemicals, or temperature changes vary, the severity of the pressure build-up to detonation can vary.

5.3.3 Syngas Production Hazards for use in FMEA

The hazards of syngas production will focus on a low carbon emissions methodology of creating syngas. The feedstocks for this production will be carbon dioxide captured by selexol solvent from atmosphere and hydrogen produced from high-temperature steam electrolysis. Hydrogen production is not included as part of this accidentology analysis since it is considered that the HTEF is separate from the rest of the syngas production facility. The syngas production facility is considered to include the selexol carbon dioxide capture and the RWGS reaction. The complete FMEA results for syngas synthesis is listed in Appendix C. The main hazards include fire, explosion, and toxicity.

The FMEA is structured to provide a comparison with hydrogen production FMEA, because syngas synthesis relies on hydrogen generated from an assumed HTEF. The similarities between syngas and hydrogen originate from the flammable nature of both gases, although hydrogen has a wider range of flammability and higher heat of combustion. A key difference between the two is that, unlike HTEF, syngas synthesis does not require steam from the ANPP Therefore, a syngas production facility can be situated farther away from the ANPP instead of being co-located.

A leak or fire at the syngas facility is less likely to affect the nuclear power plant. However, it is important to note that syngas is a denser gas than hydrogen. While leaked hydrogen is dispersed easily into the atmosphere, syngas may be carried by the wind while undergoing a slow diffusion process. There is some probability that the wind could blow in the direction of the ANPP, transporting leaked syngas. If the syngas concentration is above the lower flammability limit and it meets an ignition source at the ANPP complex, a syngas fire can occur there. Additionally, syngas also poses a toxicity hazard due to its carbon monoxide content, which can restrict outdoor operations even if there is no fire.

5.3.4 Refinery Plant Hazards for use in FMEA

The FMEA for a nuclear-integrated refinery has been performed for the four perspectives, as mentioned above and documented in Appendix D.

For ANPP safety, the hazards from the co-located refinery plant to the nearby ANPP are analyzed and included in the FMEA in addition to the hazards associated with the ANPP operation itself. For the refinery hazards, both actual historical accidents and hypothetical events discussed with SMEs are included in the FMEA. For public perception, all the events in the FMEA from ANPP safety and refinery are analyzed. The frequency and detection are the same as those assigned in ANPP safety and refinery, but the severity is different based on the level of the public concerns that arise for each of the event. A similar approach is used for the FMEA of economic impacts, where different severities ranging from 1 to 10 are assigned based on the potential revenue losses associated with each event.

Petroleum refineries are complex, high-valued facilities that process large volumes of flammable crude oil to produce large volumes of product fuels. To operate profitably and safely under environmental policies and constraints, refineries efficiently integrate steam and power demands within all the refining processes into a single, self-sufficient process. Each step along the refining pathway, from raw material storage to finished fuel production and storage, includes multiple processes that may pose a threat to the facility, environment, and workers as well as the residents close to the facilities. The inherent properties of feedstocks, intermediate streams, and finished fuel products pose severe fire, explosion, chemical exposure, and toxicity hazards. The operating condition of the refinery process involves high-temperature and pressure hazards. Table 5-4 summarizes the hazards associated with the refining processes, including crude processing, intermediate stream conversion and upgrading, component blending, and product storage.

Table 5-4. Refinery hazard summary.

Process/Storage Unit	Hazards
Crude Oil Fractionation	Fire, high temperature, chemical exposure
Coking	Fire, high temperature, toxicity
Fluid Catalytic Cracking	Fire, high temperature, toxicity
Hydrotreating/Hydroprocessing	Fire, explosion, high temperature, pressure, chemical exposure, toxicity
Alkylation	Fire, explosion, high temperature, pressure, chemical exposure, toxicity, corrosive chemicals
Sulfur Plant	Fire, explosion, high temperature, chemical exposure, toxicity
Hydrogen Plant	Fire, explosion, high temperature
Fuel Gas Treating	Fire, explosion, chemical exposure, toxicity

From Table 5-4, the hazards for the refinery process include fire, explosion, high-temperature exposure, chemical exposure (e.g., hydrogen sulfide, naphtha), and overpressure events. Sensors can detect when chemicals leaks occur and can, in turn, provide the staff with time to ignite flares and prevent a larger accident, shut down equipment safely, and evacuate the area. However, there are many cases of documented events, especially fires and detonations, that have occurred without sufficient warning. Fire, explosions, high-temperature exposure, and overpressure events may impact the facilities and staff in both refinery plants and co-located ANPPs depending on the distance from and location of the ignition points and the availability of the safety systems. The consequences of these events can include the loss of lives, injuries, and damage to the industrial facility. Fire or explosions from the refinery site occur due to hot work around tanks and ignition sources present when a leak occurs. Sometimes the leak cannot be detected fast enough to prevent an accident. Once the accident occurs, it can be easily detected on-site because the ignited fire and explosions usually come with flame and smoke or sounds. Chemical exposure poses a concern when undetected toxic chemicals are released to the environment. It is best to rely on electronic sensors to alert on-site staff of toxic chemical presence. Carbon monoxide, syngas, and hydrogen sulfide are examples of toxic chemicals found in the industrial sites under consideration. Hydrogen sulfide is an example of a toxic chemical that can be detected easily on-site by sensors due to its specific odor, even though it is colorless [2]. However, it is toxic at low levels of concentration in air and failing to detect the hydrogen sulfide poses a health hazard for workers, first responders, and residents nearby. While the hydrogen leakage does not cause long-term impacts on the health of the on-site staff and nearby residents, its high flammability can cause potential fires and explosions. If these events occur in close enough proximity, and with enough severity to affect the ANPP, there may also be loss of lives, core damage, radioactive chemical release, economic loss, and impacts on public opinion of ANPP safety.

5.3.5 Pulp and Paper Mill Hazards for use in FMEA

The hazards for pulp and paper plants in terms of storing the feedstocks, processing, and finished product storage areas are summarized in Table 5-5, which highlights the potential hazards associated with during the process or locations in the facilities.

Table 5-5. Full-process kraft mill pulp hazards summary.

Process or Location	Hazard
Woodyard	Fire
Storage	Fire
Bale and Finishing	Fire
Digesting	Explosion, chemical exposure

Recovery Boiler	Explosion, fire, chemical exposure
Paper-Making Machines	Fire
Power Plant	Fire
Bleaching	Explosion, chemical exposure
Finishing	Fire, chemical exposure
Converting	Fire

From Table 5-5, the hazards include fire, explosion, and chemical exposure. The fire and explosions hazards are relatively easy to detect based on the flame and smoke, along with the sounds from the ignition sources. Chemical exposure poses both toxic and non-toxic concerns.

The FMEA for a pulp and paper mill neighboring an ANPP is divided into four segments identifying potential failure modes within the mill operations to assess the potential effects of these failures on the adjacent ANPP, the pulp and paper mill itself, public impact and perception, and the economic wellbeing of the operation. The FMEA results are found in the tables of Appendix F. Facility processes were systematically evaluated to uncover any potential for failure that could lead to downtime, compromise safety, or impact the ANPP, public health, and perception, or the economics of the facilities. Multiple facets of the mill's operations were considered, from the mechanical aspects of the pulp processing machinery to the chemical treatment stages and waste management systems.

Pulp and paper mills are prone to several hazardous incidents, with explosions, fires, and chemical exposures or leaks among the most severe. Recovery boilers, where chemicals are burned to recover pulping chemicals, are especially explosion-prone areas due to the high-pressure conditions and volatile substances involved. Fires are potential risks in multiple areas of a pulp and paper facility, such as the woodyard or inside the paper machines where overheating equipment can ignite paper products. Chemicals like the bleaching agent chlorine dioxide and the pulping byproduct “black liquor” pose particularly concerning health risks to workers and the environment when mishandled. Accidental releases of these substances can lead to toxic exposure, causing severe injury or fatality and can have devastating environmental impacts if they enter waterways.

The FMEA conducted on a pulp and paper mill near an ANPP has identified various hazards. Some hazards, such as machinery malfunctions and localized chemical exposures, are mainly contained within the mill. However, others have the potential to extend beyond the mill's boundaries. For example, the accidental explosive potential of recovery boilers and digesters could exert enough force to impact nearby structures. Additionally, the use of hazardous chemicals such as chlorine dioxide or black liquor not only poses acute health risks to employees in the event of a leak but also brings the risk of environmental contamination. If these chemicals were to contaminate shared water sources, the effects could extend to public health and the ANPP. Although these issues are concerning, establishing a safe siting distance could help prevent potential consequences from reaching the ANPP.

5.4 Nuclear Power Plant Safety-Critical Structures

The reactor building is the primary critical structure at an ANPP. It is also the most well-protected from any external forces, such as blast impulse shock waves. Nuclear-grade concrete walls encase the containment and provide significant protection from external forces to the reactor internal structures in addition to providing significant protection from accidental release of ionizing radiation. Critical structures external to the reactor building are typically designed to withstand postulated extreme local wind and seismic loads. These include coolant storage tanks and passive safety systems inlets and outlets. No attempt was made to evaluate missiles created by an industrial facility overpressure event because that is a site specific analysis.

5.4.1 Reactor Containment Structure Fragility to Overpressure Events

Reactor building concrete walls were characterized in EGG-SSRE-9747, "Improved Estimates of Separation Distances to Prevent Unacceptable Damage to ANPP Structures from Hydrogen Detonation for Gaseous Hydrogen Storage" [30]. The lowest static pressure capacity of nuclear concrete identified is 1.5 psi. This conservative estimate was used for the blast analyses performed in prior hydrogen plant separation studies by INL [31],[32], and is adopted as the static pressure capability of nuclear concrete walls in this study as well.

NRC Regulation Guide 1.91 [3] uses a 1.0 psi overpressure when calculating safe separation distances from potential explosion sources outside of the OCA to the nearest ANPP SSC. It is not expected that this regulation will change for ANPPs. The site's FPP and the standards that are referenced within will dictate safe separation distances from any fire or explosive sources within the OCA.

5.4.2 Safety-Critical External Structures Fragility to Overpressure Events

Critical structures outside of the reactor building have been identified when assessing external events such as high-wind fragility for PRA.

External water tanks are located close to the reactor building to provide condensate storage and coolant for routine, refueling, and emergency operations. In some cases, there are concrete walls placed around the external tanks for protection, but some ANPPs choose not to include external protection other than the tank's own construction. These tanks are built to extreme standards. According to Reference [33] and other individual plant examinations of external events, they are equivalent in structural integrity against wind pressure to a Category I Structure. This means that the tanks are nearly as durable as the reactor building itself and nearly as durable as reactor containment when it comes to handling pressure. The CST and other storage tanks are assumed to be Category II structures when considering susceptibility to wind missiles.

Service water intakes are solid structures, and their failure modes typically involve the buildup of debris on the screens instead of physical damage; and the pump house is typically built to withstand tornadic or hurricane winds. In some ANPP PRAs, a loss of service water is itself an initiator that challenges the ANPP to shut down safely.

Depending on the ANPP design, loss of switchyard components could mean a LOOP event that challenges the ANPP to shut down safely. Switchyard components are sensitive to wind pressure, and particular care needs to be taken to ensure facility location provides a safe separation distance between the source of an explosive overpressure event and these SSCs.

5.4.3 Non-Safety-Critical External Structures

In addition to critical structures, some other structures that affect operations, but not typically the ability to safely shut down the reactor, are located in the plant yard as well: circulating water and standby service water pump houses, demineralized water storage tank(s), cooling towers, well water pump houses, liquid nitrogen tanks, and hydrogen and nitrogen gas cylinders, which present stored energy in the form of chilled and pressurized gas.

Further, the day-to-day ANPP operations would be affected by damage to the turbine building, administrative building, and maintenance support buildings located throughout the site.

5.4.4 Heat Extraction System Unisolable Steam Pipe Rupture

A large steam line break is the most common hazard introduced by adding the HES to the ANPP. An example of an LWR NPP system was provided in Reference [11] and may have some application to ANPP HESs. There is one non-nuclear safety (NNS) related isolation valve immediately after the steam tap for each of the HES designs listed in Section 4.1 of Reference [11]. Although not credited in any accident analysis response scenario based on its NNS classification, the success of this valve is the first line of defense of a steam line rupture within the HES after the LWR NPP's MSIVs have failed to isolate. Isolation and control valve ruptures are also a possibility that need to be modeled. After the isolation valves, all the other active components listed in Section 4.1 of Reference [11] are evaluated in the HES FTs (Sections 6.2 and 6.3). The FT result was added to the IE for a large steam line break, as described in Section 6.2.1 for a PWR and Section 6.3.1 for a BWR [11].

Seismic considerations may be added to the IE for a large thermal line break. This includes loss of function of the valves due to a seismic event. The PRA logic includes options for seismic events in five bins ranging from a peak ground acceleration of 0.17 to 2.12 g. Bin frequencies and gamma uncertainty distribution parameters utilized are from the NRC generic BWR and PWR models. These are reported in Table 5-6.

Table 5-6. Seismic bin peak ground accelerations and frequencies.

Bin #	Peak ground acceleration (g)	Frequency (/yr)	r of gamma
1	0.17	7.23E-05	3.00E-01
2	0.39	6.49E-06	3.00E-01
3	0.71	2.29E-06	3.00E-01
4	1.22	2.74E-07	3.00E-01
5	2.12	9.60E-08	3.00E-01

Extensive searches on seismic fragility constants were performed and the best data found was for residual heat removal motor operated valves and feedwater check valves from Reference [34]. The fragility constants and the valves they were applied to are documented in Table 5-7. Note that these valves are for LWR components and may not be representative of similar valves operating on fluids other than process steam. This is presented as a possibly applicable sample.

Table 5-7. Seismic fragility constants for valves evaluated in LWR main steam line break.

Valve Type	Seismic Lognormal Fragility Constants		
	Am (g)	βr	βu
Gate valve as a motor operated valve (MOV)	3.10	0.24	0.37
Check valve (CKV)	1.40	0.34	0.30
Flow control valve (FCV)	3.10	0.24	0.37

5.4.5 Heat Extraction System Reboiler Leak

Two types of reboiler leaks are considered for the PRA: a slow leak that is not a prompt safety concern to the ANPP operation and a reboiler rupture. The reboiler faults are considered equivalent to heat exchanger faults for the purpose of this PRA. The construction of a reboiler is more of a teakettle design than a tube-and-cartridge heat exchanger design. A reboiler design is more durable than a tube and shell heat exchanger, so using the extensive heat exchanger failure data is considered conservative in place of the lack of operational data found for reboilers.

Slow Leak of an HES Heat Exchanger: The primary heat exchange to the thermal delivery loop that leaves the ANPP could develop a small leak. Small leaks in the heat exchanger may contaminate the heat-transfer loop to the intermediate thermal facility or the industrial facility, depending on the design of the ANPP. This can cause a cleanup problem if there is enough activity transferred to the heat-transfer loop.

There are prevention, detection, and mitigation measures that need to be in place to monitor for and react to any small leaks including routine isotopic chemistry sampling. This hazard could potentially cause steam loop isolation of the industrial facility and resultant economic issues during reboiler repair and unlikely, but possible cleanup of the industrial facility steam supply.

It should be noted that most thermal delivery schemes under consideration involve a tertiary loop that would doubly protect the industrial facility thermal supply from the possibility of isotopic contamination. This study is concerned with generalized ANPP safety information and did not consider the architecture of a fully representative HES.

Rupture of an HES Reboiler: Depending on the size of the supported facility, there can be up to three HES reboilers. An HES heat exchanger rupture failure maps to the HES large steam line break event and is treated as an event within the IE FT.

5.4.6 Prompt Steam Diversion Loss Causes Feedback

The addition of the HES to the ANPP provides a new thermal loop that must be evaluated for safety. The amount of prompt thermal load loss that an ANPP can take before the upset causes the reactor to require an unexpected shut down is dependent on its design. A large enough prompt load drop could be felt by the ANPP and pushed to the turbines, even with the successful closing of the HES isolation valves. The risk analysis effort must analyze this accordingly.

5.4.7 Use of Non-Steam Heat Transfer Fluids and Ignition Potential

The use of steam as the heat-transfer medium screens this hazard out from consideration. Other options have been considered for LWRs and ANPPs. ANPPs have focused on molten thermal salts to service a tertiary steam loop that would be provided to a customer. The only hazards noted with these salts are the possibility of it freezing in the pipes or the obvious thermal energy a leak would pose locally. No toxic properties were noted. LWRs have considered the use of heat transfer fluids. A list of their properties can be found in [1] and [11].

5.4.8 Degradation of Passive Decay Heat Removal System Performance

ANPP designs are increasingly adopting passive decay heat removal (DHR) systems that rely on natural circulation and heat exchange to the atmosphere. Should an accident occur that results in the loss of external power and subsequent failure of the cooling pumps, passive systems act as a final heat sink for the decay heat. This ensures that temperatures are kept below critical levels, thereby preventing a core meltdown. However, airborne chemical clouds or debris from nearby industrial facility accidents may accumulate in the intake vents and ducts of these systems that may possibly degrade their performance and risk the nuclear reactor’s safe shutdown capability. Argonne National Laboratory has recently published a study on various passive DHR system degradation scenarios for several DHR designs described below [35].

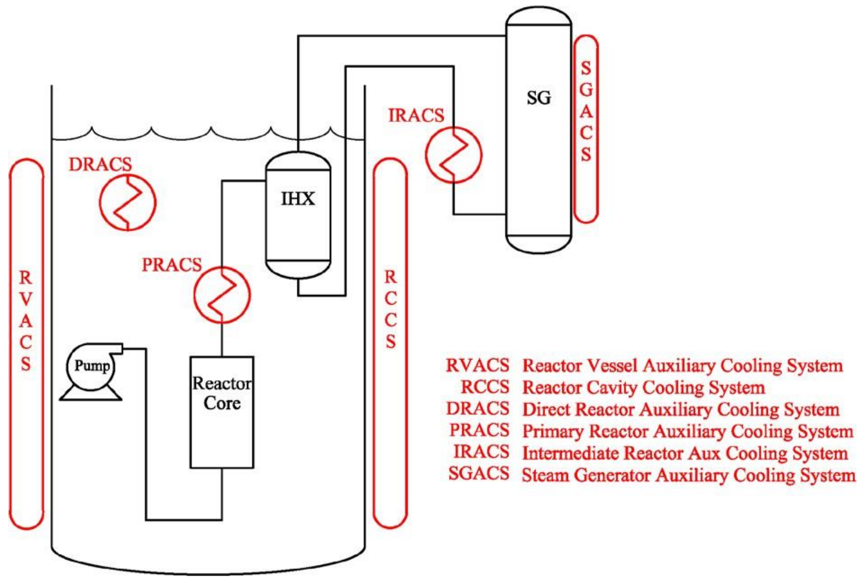


Figure 5-6. Summary of various decay heat removal systems common to sodium fast reactors (SFRs) [35]

Figure 5-6 shows the various concepts of passive DHRs common to SFRs, with some systems such as the Reactor Cavity Cooling System (RCCS) and the Reactor Vessel Auxiliary Cooling System (RVACS) also applicable to other advanced Gen IV reactor types such as HTGRs. The DHR systems can be broadly categorized into three distinct types, depending on the design of the ANPP components and cooling methods they employ, as outlined below:

5.4.8.1 Interior to Vessel Decay Heat Removal

Direct Reactor Auxiliary Cooling Systems (DRACS) function by placing heat exchangers directly into the coolant pool inside the reactor vessel to facilitate decay heat removal. This heat is then transferred through intermediate loops to the primary side of secondary heat exchangers, before being dissipated to a final heat sink using either air or water.

Primary Reactor Auxiliary Cooling Systems (PRACS) involve the extraction of decay heat from the primary system through dedicated auxiliary heat exchangers or by incorporating these auxiliary units within intermediate heat exchangers. As with DRACS, this heat is subsequently passed on to secondary heat exchangers and then dissipated using air or water cooling methods.

5.4.8.2 Exterior to Vessel Decay Heat Removal

RVACS operate by eliminating decay heat from the walls of the reactor and guard vessel through convection and/or radiation. This heat is then conveyed to the air circulating within the concrete containment's cavity and released directly into the environment or indirectly through convective transfer to water via a secondary exchange. RVACS is mainly proposed for use in SFRs, molten salt reactors (MSRs), and lead-cooled fast reactors (LFRs).

The RCCS) functions by extracting decay heat through radiation and/or convection straight from the reactor pressure vessel (RPV) walls into a system of air or water-filled standpipes. These standpipes are situated within the concrete containment, at a certain distance from the RPV. In contrast to the RVACS, the RCCS offers an extra layer of isolation between the reactor containment and the secondary coolant. RCCS designs can either operate passively through natural circulation or actively under normal conditions, switching to passive mode in the event of an accident. RCCS is mainly proposed for use in HTGRs.

5.4.8.3 Secondary or Intermediate Decay Heat Removal

The Intermediate Reactor Auxiliary Cooling System (IRACS) involves the removal of decay heat via a heat exchanger that is integrated into the secondary coolant circuit. This heat is then conveyed through specialized intermediate loops to heat exchangers that are cooled by air.

5.4.8.4 Passive Decay Heat Removal Degradation Evaluation

Of the systems listed, two were evaluated for degradation potential, the RCCS and the RVACS. The various abnormal and degraded passive DHR conditions investigated in reference [35]:

RCCS Abnormal and Degraded Conditions

- Blockage of riser flow channels. This experiment was done by blocking a number of riser channels up to 50% of the available RCCS riser channels. As the system's total flow rate decreased in each phase, the authors noted that the facility's effectiveness in removing heat remained mostly consistent. The temperature of the heated plate, which simulates the reactor pressure vessel (RPV) walls, maintained an average of 279°C during normal operation with all channels open and increased to 292°C when 50% of the channels were blocked. These slight increases in RPV temperature indicate a strong reliability in the system's heat removal capabilities, even when some of the riser channels are obstructed. This degradation scenario represents what may happen to RCCS from the pulp and paper mill industry, as wood pulp debris accumulates in the air intake vent. It is unlikely for this debris accumulation to cover more than 50% of HTGR RCCS riser channels, as there are several redundant channels and debris accumulation is a slow process such that it can be detected long before it significantly reduces the RCCS air flow.
- Flow path short circuit. In this scenario, a break occurs between adjacent ductwork that allows incoming cold air to by-pass the heated section and instead flows directly back into the exhaust stream. Break areas of up to 100% nominal single duct flow areas were studied. The authors concluded that these breaks may severely degrade the heat removal performance of the air-based RCCS system and could result in severe impacts to system temperatures. However, it is unlikely that nearby industrial processes could cause this event.
- Non-air gas ingress. The experiment was done by feeding high purity argon gas representing heavy gases to the RCCS intake vent following a steady-state normal operation of the nuclear reactor. The amount of argon gas used was twice the internal volume of the total facility flow path. The authors noted a rapid decline in system flow rates to almost zero within roughly 90 seconds following the start of the argon influx event, leading to a near-complete cessation of flow that lasted about 18 minutes. As a result of the halted fluid movement and the compromised ability to remove heat, temperatures of both the fluid and the structure started to climb significantly. This temperature increase created a driving force that restarted the buoyancy-induced flow after 18 minutes. This phenomenon allowed the facility to gradually return to its normal operation as the argon was purged from the system. A nearby industrial facilities may possibly cause this event if there is a fire with thick smoke that happens to blow towards the RCCS vent openings. However, it can be reasonably hypothesized that the likelihood for this event is sufficiently low, since fire smoke tends to drift upwards instead of behaving like a heavy gas, and it is dispersed along the downwind direction. Smoke concentration may accumulate if the atmosphere is stable and there is an inversion layer.

RVACS Abnormal and Degraded Conditions

- Blockages of air inlets and outlets. The experiment studied various postulated RVACS air blockages at the air inlets and outlets, of up to 75% area blockage of each air inlet and outlet openings on a 4-inlet 4-outlet RVACS. Results show that at the worst scenario, the maximum core outlet temperature increased only 32 ºF (18 ºC), suggesting that nuclear reactor safety is not challenged in this scenario.

This scenario is unlikely to be caused by nearby industrial facilities for the same reason stated for the blockage of RCCS riser flow channels.

- Removal of RVACS air stacks. This experiment assumes a postulated major external event that take out up to three air stacks from the 4-stacks system. The removal of three stacks increased the maximum core outlet temperature by 101 °F (56 °C) to 1226 °F (663 °C). Regardless, it is still below the service level temperature limit of 1350 °F (732 °C), suggesting that the reactor will still be safe in this scenario. This event is unlikely to be caused by nearby industrial facilities, but rather perhaps by a major hurricane or a major earthquake.
- Complete blockage of air inlets. In this scenario, all four air inlets are completely blocked while the four air outlets remain fully open. Results show that half of the air outlets functioned as cold air inlets, and that the maximum core outlet temperature increased to 1168 °F (631 °C) which was still below the design basis temperature limit of 1250°F (677°C). It is unlikely for nearby industrial processes to cause this event, since the four inlet vents typically face different directions. Furthermore, debris or soot accumulation on inlet vents is a slow process that would have been detected and remedied long before it blocks all the inlets completely.
- Complete blockage of air outlets. Similarly, a complete blockage of all four air outlets while the air inlets were open was also studied. This scenario led to a worse situation than the complete blockage of inlets, where the core outlet temperature reached 1,393 °F (756 °C) after 13 hours following the blockage. However, this scenario is less likely to happen than the blockage of air inlets, because there is a driving force of hot air exiting the outlets at about 5 ft/sec (1.5 m/s) with a temperature of 190°F (87.8°C) that would prevent debris to sit and accumulate at the outlet vents. Even if the outlets are blocked, a small portion of airflow leaking through the outlets would result in increased cooling and an acceptable situation.
- Complete blockage at the bottom of silo. This scenario assumes a complete blockage of RVACS air flow path at the bottom of the reactor silo that could happen due to a partial collapse of the concrete silo wall or a severe sandstorm. However, even these assumptions are overly conservative because rubble or sand still possess some permeability to airflow. Should this type of blockage occur, half of the air outlets will function as air inlets and decay heat will be removed safely. Furthermore, some cooling can also be attributed to the cold air downcomer, resulting in an even better outcome compared to the blocked inlet scenario. This scenario is unlikely to be caused by nearby industrial facilities as it requires a large amount of mass (e.g., debris, soot, sand) to fill the bottom of the silo and block RVACS air flow.
- Reactor silo water seepage. This scenario assumes that water finds its way into RVACS and fills the bottom of the silo, reducing and even blocking the air flow. Results show that RVACS performance is not significantly affected when silo is partially flooded with water because RVACS air flow removed water at a rate more than 1 ft depth per 24 hours. If the water level completely blocks the flow, the hot containment vessel transfers enough heat to boil the water pool, removing both decay heat and water mass significantly. It is unlikely for this scenario to be caused by nearby industrial facilities.

Table 5-8 summarizes all the investigated passive DHR degradation scenarios as discussed above. As the table shows, it is improbable for surrounding industrial installations to impact the performance of passive DHR systems in a way that would jeopardize the safety of the nuclear reactor.

Table 5-8. Summary of investigated passive DHR degradation scenarios.

System	Degradation Scenario	Reactor Status	Likelihood to be Caused by Nearby Industries
RCCS	Blockage of up to 50% of riser flow channels	Safe	Remote
	Short circuit of up to 100% flow path	Unsafe	Remote
	Non-air heavy gas ingress up to 2x the internal volume of the total facility flow path	Safe	Low
RVACS	Blockages of up to 75% of each air inlets and outlets	Safe	Remote
	Removal of up to 3 air stacks	Safe	Remote
	Complete blockage of all air inlets	Safe	Remote
	Complete blockage of all air outlets	Unsafe	Remote
	Complete blockage at the bottom of silo	Safe	Remote
	Reactor silo water seepage	Safe	Remote

5.5 Industrial Facility Siting Analysis

The placement of the industrial customer is determined first and foremost by the safety of the ANPP and the public. Other considerations are made due to the geographical properties of the proposed ANPP site, the proximity to the heat exchanger building to make the steam supply line as efficient as possible, and the accessibility of the industrial customer for transport of the final product. The following sections provide analyses useful to visualizing the inherent risk evaluation aspects for industrial customers considered in this report, the standoff distances required for these hazards and plant sizes, and where in the industrial customer facilities these hazards are located.

It is noted that operating U.S. NPP's were all originally evaluated for the risks of nearby industrial facilities such as in RG 1.91 [3] and other then-accepted NRC methodologies under original licensing agreements. Similar risk analyses will be agreed upon for proposed locations of ANPPs sited to maximize energy transfer from an ANPP in the form of electrical, heat, or hydrogen to new industrial users. The sections that follow identify topical evaluation areas but are not necessarily intended as approved approaches that will be accepted by the NRC.

5.5.1 Blast Analysis

The major accidents in industrial installations are usually related to a loss of containment that releases hazardous materials. Following the discharge, how the situation unfolds will be influenced by the physical form of the released substance and other factors, such as the volume of the substance spilled and prevailing weather conditions. Figure 5-7 shows the possible scenarios following a hazardous material release [36].

A liquid spill can contaminate the soil and/or body of water. It can also evaporate or catch fire if it is flammable and it meets an ignition source, probably by igniting the vapor cloud. The combustion can release smoke, thermal radiation, and overpressure. Alternatively, a flammable or toxic cloud may develop if no immediate ignition occurs. The flammable cloud can ignite and produce a flash fire and thermal radiation hazard. Depending on the amount of material and degree of confinement, a flash fire may lead to an explosion, causing overpressure and missiles.

Meteorological conditions, including wind, can contribute to the creation of a toxic vapor cloud. When a hot, pressurized liquid is emitted into the atmosphere and instantaneously vaporizes, it often results in a vapor-liquid blend that can lead to a dense vapor cloud due to the evaporation of liquid droplets, thereby elevating the concentration of the vapor in the air.

A gas or vapor release can lead to cloud formation if the release velocity is low. However, if the release is at a high velocity, the resulting air entrainment will dilute the mixture, causing it to disperse in the atmosphere making the formation of a flammable cloud unlikely. Should ignition take place, there is a risk of a jet fire occurring in both scenarios.

Dust released into the atmosphere can pose hazards such as allergenic reactions. Additionally, fine dust can lead to severe explosions if dispersed in the air within an enclosed space. These explosions typically happen inside equipment like silos, dryers, or cyclones, rather than from a containment breach, but their impacts can still extend over a large area.

If the pressure within a pressurized tank exceeds a certain threshold or if the tank's integrity is compromised due to high temperatures from a fire, an explosion can occur. This explosion would impact the surrounding area and could launch debris over great distances. Should the contents be flammable, it's likely that the explosion, which might be a Boiling Liquid Expanding Vapor Explosion (BLEVE), would be accompanied by a fireball.

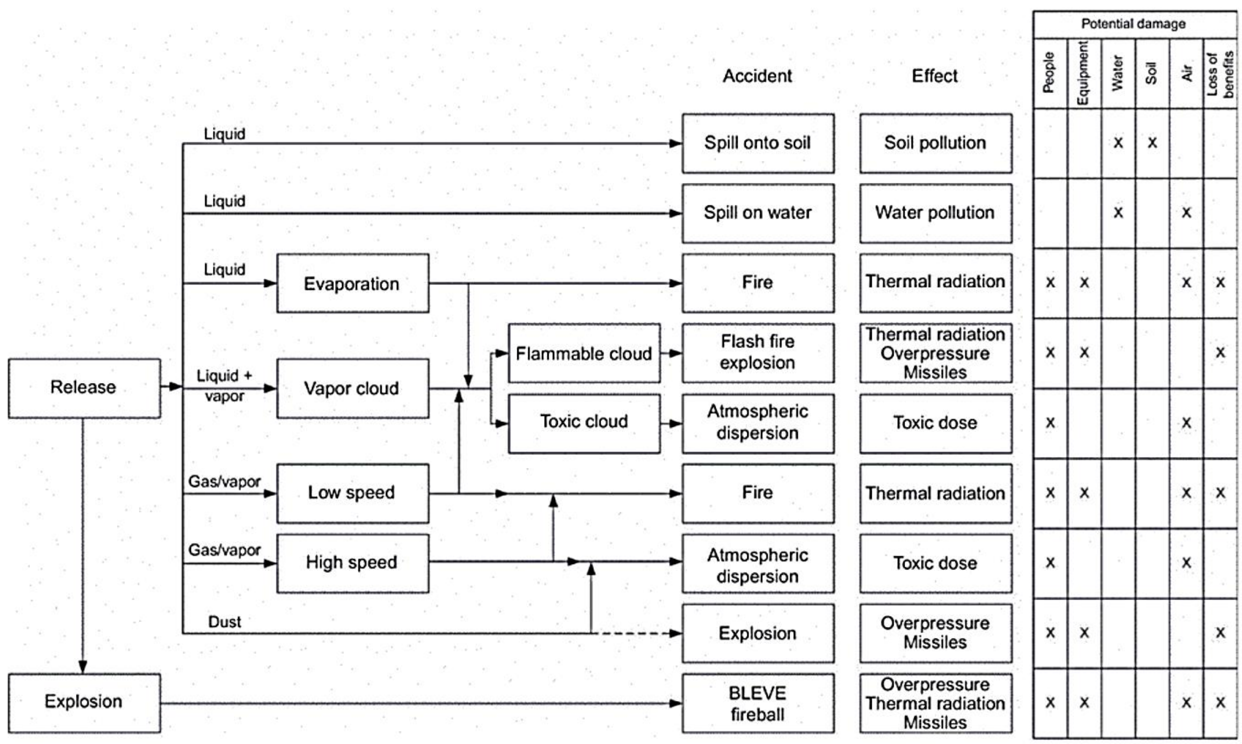


Figure 5-7. Schematic representation of possible accidents following a loss of containment [36].

Industrial facilities are designed such that fire and explosion hazards are limited within their safe boundaries. However, vapor clouds have the potential to traverse outside the boundaries before meeting an ignition source. Therefore, special consideration is given to atmospheric dispersion and vapor cloud explosions (VCEs) in this Section.

For a VCE to happen, certain criteria must be met [36]. The substance should be combustible, and the ignition must be delayed for a cloud of fuel-air mixture to form. Otherwise, an immediate ignition causes a jet fire instead. A portion of the cloud mixture must also fall within flammable limits, making it capable of ignition. The vapor cloud additionally needs to reach a minimum size, and there must be turbulence present, which can be caused by the manner of the release, such as a jet, or by interaction with obstacles that lead to partial confinement. This confinement and congestion are important because they are commonly present in industrial installations, which creates favorable conditions for slow deflagrations to accelerate in what is known as flame acceleration resulting in more severe explosive cases [37].

The mechanical energy from an explosion generates an overpressure wave that travels through the atmosphere at a specific speed. This wave is created by the opposing forces of the increasing pressure from combustion and the decreasing pressure caused by the expanding gases. There are various methods to calculate this blast overpressure, with the empirical models being the most popular options due to their simplicity and reliable results [37]. Empirical models, which are based on data from numerous experiments, allow for quick calculations of pressure and impulse from explosions using layout and thermodynamic information about the flammable mixture. They are particularly useful in the preliminary design phase of new facilities, which is the scope of this current study. However, many of these models do not provide direct guidance to assess deflagration to detonation transition (DDT) likelihood, which may lead to underestimations of explosion severity. Therefore, it is recommended that additional methods are used to evaluate DDT events on mature, site-specific industrial facility designs.

Among the various empirical methods to calculate unconfined blast overpressures, three methods are of particular interest in this study: the Bauwens-Dorofeev method, the TNT equivalent method, and the Baker-Strehlow-Tang (BST) method. These methods use separate families of empirical blast curves.

The Bauwens-Dorofeev method calculates the blast overpressure based on the amount of detonable mass within the cloud. A key feature of interest in this method is that it has empirical polynomial equations to calculate the detonation cell size and eventually the detonable mass of common flammable gases, including hydrogen, methane, and propane [38]. The available hydrogen data is extensive, which gives a good confidence in hydrogen blast overpressure calculations. The detonable mass (m_{det}) is used to calculate the detonation energy (E_{det}) according to Equation (3), where H_c is the heat of combustion. Detonation energy is used to calculate a set of dimensionless distance ($R^*_{Bauwens}$) from the center of the detonable region according to Equation (4), where R is a set of distance values and $P_{ambient}$ is the ambient pressure. This set of dimensionless distance is used to calculate the corresponding set of scaled overpressure (P^*) using the empirical Equation (5) [38].

$$E_{det} = m_{det} H_c \tag{3}$$

$$R^*_{Bauwens} = R\left(\frac{P_{ambient}}{E_{det}}\right)^{1/3} \tag{4}$$

$$P^* = \frac{0.34}{(R^*)^{4/3}} + \frac{0.062}{(R^*)^2} + \frac{0.0033}{(R^*)^3} \tag{5}$$

The TNT mass equivalence method is the simplest means of modeling VCEs. It works by finding the equivalent mass of TNT containing the same energy as the combusted fuel [38]. The interest in this method is that it is prescribed by existing nuclear regulation to calculate the safe distance at which the overpressure drops to 1 psi [3]. This 1 psi limit is also prescribed in the Environmental Protection Agency (EPA) citing the U.S. Code of Federal Regulations for chemical accident prevention [39], although its quantification methodology is not specified. The TNT equivalent mass is scaled by an equivalence factor (F_{equiv}) as shown in Equation (6), often also called yield factor, efficiency, or efficiency factor. In a sense, this TNT equivalency informs the efficiency of energy conversion from chemical combustion into mechanical blast. The theoretical maximum equivalency is 40%, however the empirical equivalency is proposed between 1 to 20% according to different authors [40]. The NRC adopts equivalency factors from FM Global [41] (i.e., 5% for unconfined combustible gases and vapors such as hydrogen, 10% for unconfined combustible dusts, and 15% for unconfined ignitable fibers [3]). Meanwhile, the EPA prescribes an equivalency of 10% for flammable gases and liquids [39].

$$E_{TNT} = F_{equiv}E_{fuel}$$
$$m_{TNT}H_{c,TNT} = F_{equiv}(m_{det}H_c)_{fuel} \tag{6}$$
$$m_{TNT} = F_{equiv}\frac{(m_{det}H_c)_{fuel}}{H_{c,TNT}}$$

The TNT mass equivalent is used to calculate a set of scaled distances (R^*) using Equation (7), and the scaled overpressure (P^*) is found from an empirical curve relating P^* to R^*.

$$R^*_{TNT} = \frac{R}{m_{TNT}^{1/3}} \tag{7}$$

The BST method assumes that only the parts of the flammable cloud that are congested or partially confined contribute to the overpressure buildup [35]. The appeal of the BST method is that it is one of the few empirical methods that provides direct guidance to assess DDT likelihood [37], which is when the flame speed reaches at least Mach 5.2 [42]. BST analysis consists of these steps [35]:

5. Calculate the volume of a cloud containing the mass of fuel at the stoichiometric concentration.
6. Identify the volume of the congested or partially confined portion of the flammable vapor cloud.
7. Calculate the explosion energy (E) by multiplying the volume of the congested or partially confined portion of the flammable vapor cloud by 3.5 MJ/m^3.
8. Calculate the set of scaled distances (R^*) from the center of the explosion using Equation (8).

$$R^*_{BST} = \frac{R}{(E/P_0)^{1/3}} \tag{8}$$

9. Select the appropriate flame speed (Mach number) from the values listed in Table 5-9 based on the fuel and congestion levels.

Table 5-9. Flame speed Mach numbers (M_f) of BST method.

Fuel reactivity	**Congestion level**		
	Low	**Medium**	**High**
High: hydrogen, acetylene, ethylene oxide, propylene oxide	0.36	DDT	DDT
Low: methane, carbon monoxide	0.026	0.23	0.34
Medium: all other gases and vapors	0.11	0.44	0.5

10. Use the BST empirical curves to obtain the dimensionless peak side-on overpressure based on R^*_{BST} and M_f from steps 4 and 5.
11. Convert the dimensionless side-on peak overpressure to the peak side-on overpressure by multiplying it by the atmospheric pressure.

A comparison of blast overpressure and safe separation distances between the Bauwens-Dorofeev and the TNT equivalence method was conducted in a previous study for the pre-conceptual hydrogen HTEF designs under consideration [1]. The results summarized in Table 5-10 show that the TNT equivalence method prescribed by RG 1.91 [3] are more conservative than the hydrogen jet-leak specific Bauwens-Dorofeev method.

Table 5-10. Distance to 1.0 psi for maximum hydrogen detonation scenarios for HTEF sizes as calculated using Bauwens-Dorofeev and TNT equivalent methods.

HTEF Size (MW_{nom})	**Safe Distance (m)**	
	Bauwens	TNT
100	61	81
500	168	204
1000	215	252

Hydrogen is lightest element and is therefore dispersed easily into the atmosphere upon release. In contrast, other flammable gases may be closer to the density or denser than air and therefore have the potential to be transported downwind before they combust. For that reason, a combined analysis of atmospheric dispersion and combustion is needed to estimate these other detonation overpressure hazards to the NPP. Section 5.5.3 presents an example case of this combined analysis. Note that the atmospheric dispersion analysis is highly sensitive to site characteristics such as topology and meteorological conditions. As the current study does not target a specific site, a thorough analysis of all related industrial facilities is not performed, and only an example case study is presented. This is different for hydrogen detonation which does not require atmospheric dispersion analysis and was therefore performed in more detail.

An energetic detonation of a downwind dispersed vapor cloud is highly unlikely. However, the presence of environmental confinement and congestion may lead to flame acceleration that increases its overpressure, and in certain extreme conditions lead to a DDT. Therefore, the combined analysis in this report utilizes the BST methodology to account for these possible scenarios.

5.5.2 Blast Mitigation Strategies

Blasts that are attenuated or suppressed can be considered in many of the codes and standards that are used in fire protection plans and other regulatory codes and regulation guidelines. It is common practice in industry to place engineered barriers where appropriate.

The detonation overpressure analysis we have performed so far is for unattenuated blasts, based on the conservative assumption that there is a direct line of sight between the detonation source and the target. In practice, blast energy may be attenuated either through natural barriers such as hills, vegetation, and engineered mitigation techniques. This section summarizes several engineered methods to mitigate blast overpressure from a review study performed by SNL for this report [43]. The reference discusses three categories of techniques to mitigate overpressure energy: isolation, suppression, and attenuation.

Explosion isolation techniques aim to safeguard equipment not directly hit by an initial explosion from subsequent blasts. Mechanically, active valves shut upon explosion detection, while passive valves respond to overpressure to block a flame front from propagating to other pipe sections, as illustrated in Figure 5-8. Chemical suppression, such as the release of a chemical suppressant into pipes, is another method to halt explosion flame fronts. These methods are proactive measures for internal protection, but may be less relevant in hydrogen facilities where explosions are more likely to occur outside vessels due to the absence of oxygen inside the system. Even so, they could still offer some protection if an external blast causes flame propagation within the piping network.

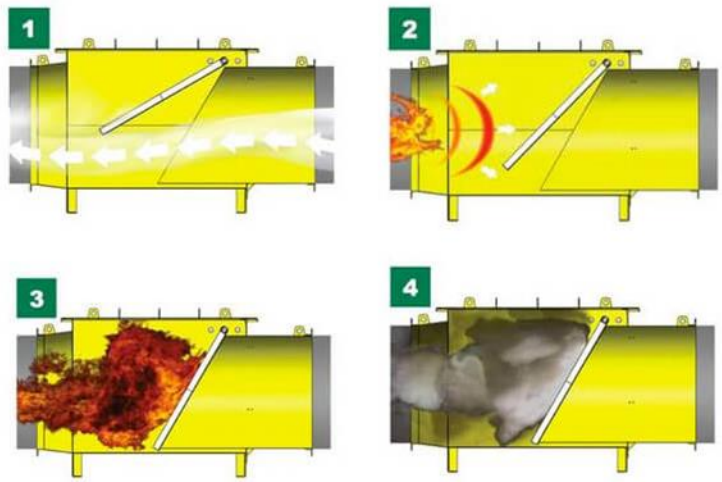


Figure 5-8. Example of a passive explosion isolation valve [44].

Blast suppression techniques are designed to either prevent ignition or slow down the flame front after ignition, with broader applications than isolation methods, extending beyond piping networks. Water mists are one such suppressant, with varying opinions on their effectiveness. Two main mechanisms are proposed: momentum transfer from larger water droplets and blast energy dissipation via the evaporation of smaller droplets, also known as quenching, which can dilute the fuel-air mix to safe levels. While some researchers see both mechanisms as valid for blast mitigation, others emphasize one over the other, citing differences in shockwave properties.

Beyond water, studies have investigated two-phase chemicals and powders as explosion suppressants. Aqueous foams can lower peak overpressure from explosions, as demonstrated in an experiment where a detonation in a plastic tent was suppressed by an aqueous foam. Additionally, commercial solutions like dry powders are available, which can be deployed into a vessel upon explosion detection to control the blast, as illustrated in Figure 5-9.

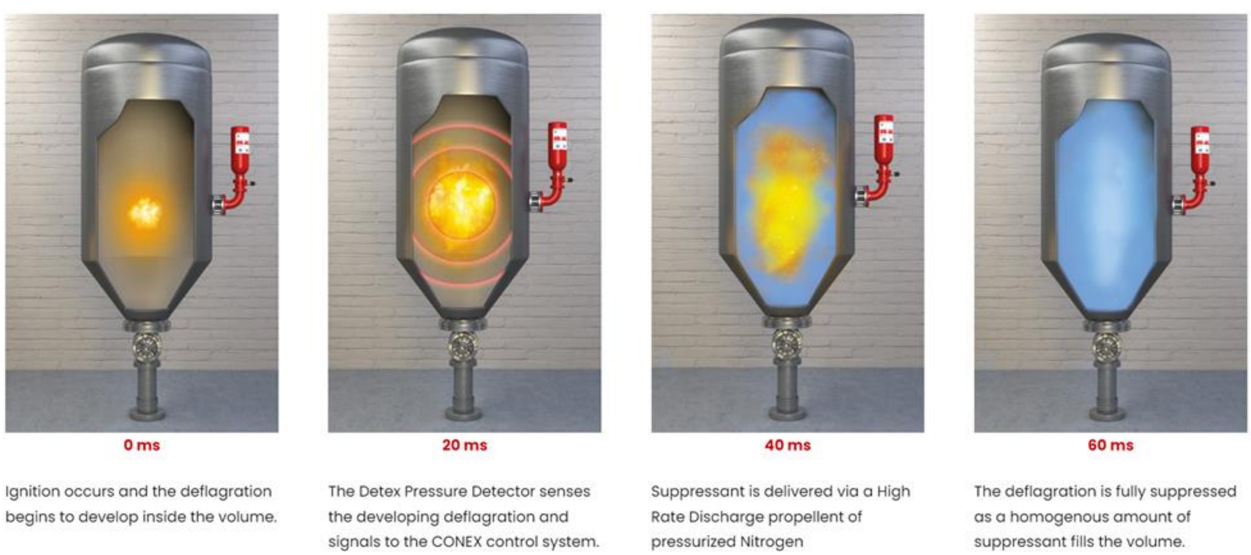


Figure 5-9. Example of an explosion suppression technique [45].

While aqueous chemicals and dry powders can mitigate blasts, applying them in a hydrogen plant is complex. Effective mitigation usually requires the explosive area to be entirely engulfed in the suppressant, which is not feasible for unpredictable hydrogen leaks. Spraying these substances when an explosion looms may not replicate tested methods and could worsen the explosion by causing more turbulence and mixing hydrogen with air. Additionally, such suppressants could be costly, difficult to clean up, and potentially harmful to the environment and nearby people, especially if granular materials are propelled by the blast. Water is considered a more suitable suppressant for hydrogen plants, provided the system design supports blast mitigation through a water deluge system.

Blast attenuation techniques aim to redirect the blast wave energy away from targets and the protected population. This objective is typically achieved by using barriers like blast walls, which utilize reflection, absorption, and diffraction to attenuate the energy that passes through the barrier.

Solid blast barriers, commonly used in oil, gas, and chemical industries, offer protection from overpressure events and propelled projectiles, with limited information on their use in hydrogen plants. NFPA 2 [18] discusses the application of blast walls in hydrogen facilities for safeguarding equipment and structures. These barriers can be either freestanding or part of existing infrastructure and are typically made of concrete or steel, with modular designs allowing for reconfiguration. Thicker concrete walls and steel reinforcement can enhance barrier durability and blast resistance. The wall's height and distance from the explosion can influence its protective efficacy; taller walls may increase overpressure within the blast area but provide more external protection, while proximity to an explosion impacts the level of overpressure and temperature experienced. Figure 5-10 shows two types of blast barriers made of concrete and metal.

Figure 5-10. Blast barriers made of modular concrete blocks (left) [46] and metal (right) [47].

Solid blast barriers can also be deployed in alternate geometries other than straight vertical walls, such as tall and thick parallelepiped, trapezoidal, triangular, and cylindrical barriers. Key geometric parameters for blast barriers include height, thickness, inclination angles of the front and rear faces, and the barrier's position relative to the blast source. Maximizing height and thickness within space and financial limits is recommended to enhance the barrier's shock wave interaction surface. The inclination angle of the wall's upstream face influences overpressure attenuation and the wall's load. A 90° inclination angle close to the blast source screens overpressure effectively but also bears a high load. Despite this, right-angle inclinations may still be preferred for their space efficiency compared to smaller angles.

Porous barriers have also been proposed, such as using metal perforated plates, chain mails, and woven wire meshes. These porous barriers can be deployed in layers to improve their efficiency.

Other materials have been investigated to act as blast barriers, including water, granular materials (e.g., sand, rock particles, polystyrenes) and sacrificial claddings. Thin plastic bags can be filled with water within a steel frame to reduce overpressure and impulse downstream. The water wall's effectiveness improved with increased height and proximity to the blast origin, mirroring the properties of a solid barrier. This solution could be cost-effective, involving only a steel frame, plastic, and water, but the water would need replacement after an event. A potential drawback is that the blast could propel water droplets that could injure people even if they are protected by the water wall. Alternatively, a water wall can be formed by a water curtain over a chain mail grid to reflect the shock wave and reduced downstream overpressure and impulse. Granular materials can also be used to attenuate shock waves. They are more effective when they consist of smaller particle diameters and are extended in length along the path of the shock wave.

Sacrificial claddings, which consist of a crushable core between two thin plates, are unique both in geometry and material compared to traditional blast barriers. Upon encountering a blast wave, the front plate moves toward the rear plate, causing the core to plastically deform and absorb kinetic energy, thereby reducing the overpressure transmitted to the rear plate and beyond. The core is typically made of a cellular material like polyurethane foam that can withstand significant plastic deformation. The cross section of this cladding is shown in Figure 5-11.

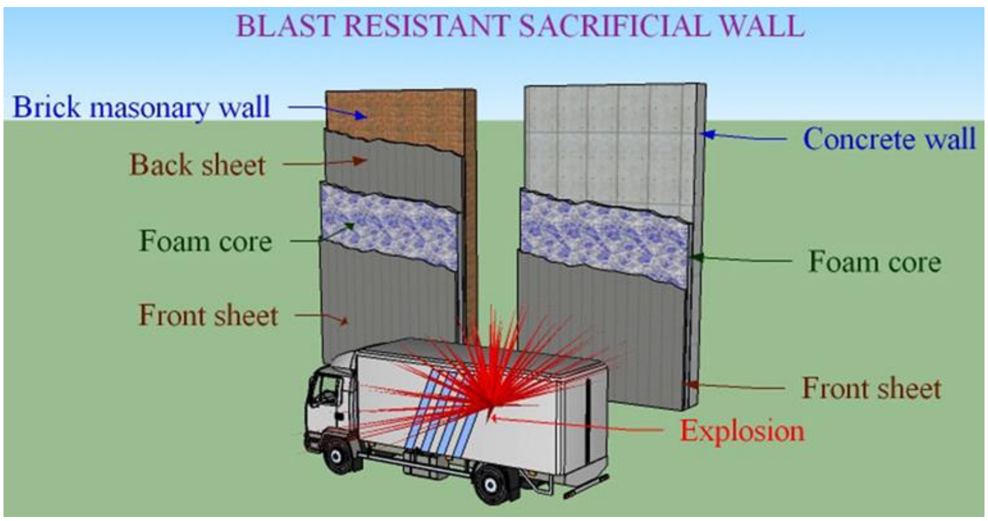


Figure 5-11. Illustration of a sacrificial blast wall [48].

Such claddings are effective in reducing overpressure and could be used for blast mitigation in hydrogen plants. However, they are single-use due to the permanent deformation from blasts and would require replacement after an explosion, potentially making them more costly than more durable alternatives. The effectiveness of sacrificial claddings also depends on having a core of adequate thickness, which varies with the unpredictable magnitude of potential blasts at a facility. Underestimating the blast load could result in insufficient protection, while overestimating it could lead to unnecessary material, cost, and space usage.

The engineered mitigation methods described above should not be the first priority in ensuring safety. Reference [43] discusses the hierarchy of control in safety management illustrated in Figure 5-12. The figure shows that the most effective way to manage hazards in hydrogen facilities is to eliminate the risk of events. This can be done by preventing hazardous gas or liquid leaks using appropriate equipment and materials, and by implementing strict leak detection, inspection, maintenance, and repair procedures. Additionally, ignition sources can be eliminated by using properly rated electrical equipment and ensuring proper grounding and bonding, as well as by enforcing no-smoking policies and providing appropriate training.

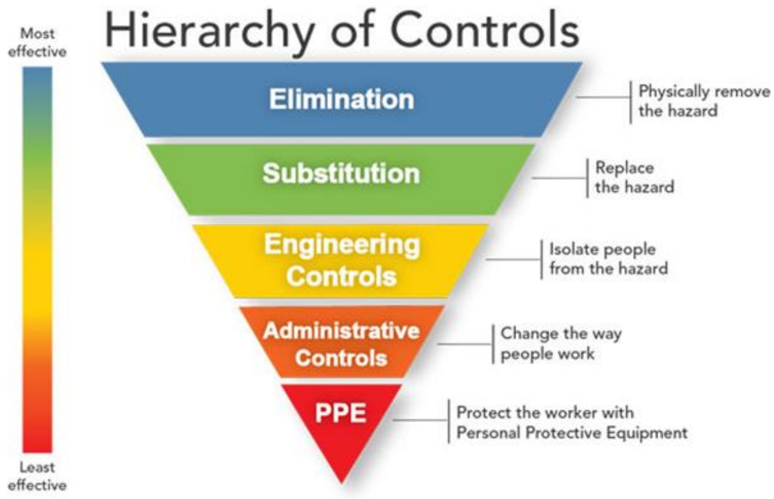


Figure 5-12. Hierarchy of controls.

After efforts to eliminate the hazard, engineering controls such as blast suppression techniques can be used to quench an explosion before it spreads. Should an overpressure event still occur, engineering controls can also isolate the hazard from people and infrastructure through blast isolation and attenuation techniques. Finally, personal protective equipment is considered the least effective means of protection in the hierarchy of controls.

5.5.3 Atmospheric Dispersion Analysis

Atmospheric dispersion analysis is needed for industrial facilities that may emit dense hazardous gases during normal operations and/or accident conditions. The purpose of this analysis is to estimate the extent of hazards extending beyond the industry perimeters that may disrupt the safe and secure operation of NPPs and/or public wellbeing. The Gaussian advection-diffusion model is used in this analysis with possible benchmark with other models in future studies. This study uses the ALOHA [43] [49] free software tool by developed by the EPA. ALOHA adopts the Gaussian dispersion model which is commonly used for accident response planning. Benchmark analysis using other dispersion models may be done in future studies.

5.5.3.1 Dispersion Modeling in ALOHA

The Gaussian model suggests that, as the distance downwind grows, the concentration profile of a continuous release of gas with neutral buoyancy will converge toward a Gaussian distribution as illustrated in Figure 5-13. The gas plume diffuses along the y and z axes to converge toward a Gaussian distribution as it is transported through advection along the x-axis direction. Longer measurement averaging periods not only encourage a Gaussian configuration but also expand the spatial extent of the distribution.

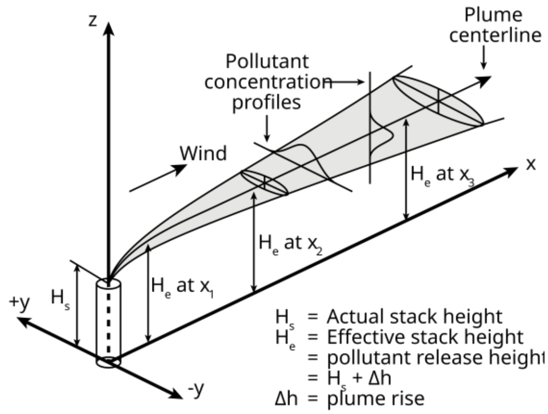


Figure 5-13. Illustration of Gaussian dispersion model [50].

The concentration of a gaseous mixture following a short release is given in Equation (9) as follows [42]:

$$C(x,y,z,t) = \begin{cases} \dfrac{\chi}{2}\left[erf\left(\dfrac{x}{\sigma_x\sqrt{2}}\right) - erf\left(\dfrac{(x-\bar{u}t)}{\sigma_x\sqrt{2}}\right)\right] & (t \le t_r) \\ \dfrac{\chi}{2}\left[erf\left(\dfrac{x-\bar{u}(t-t_r)}{\sigma_x\sqrt{2}}\right) - erf\left(\dfrac{(x-\bar{u}t)}{\sigma_x\sqrt{2}}\right)\right] & (t_r < t < \infty) \end{cases} \quad (9)$$

Where σ_x is the dispersion parameter and t_r is the duration of the release.

ALOHA uses the Gaussian dispersion model of continuous air pollution flumes, and the heavy gas model for gases or aerosols that are heavier than the surrounding air. This heavy gas model is illustrated in Figure 5-14. Initially, a heavy gas cloud will settle away from its origin point in every direction due to being denser than the ambient air. Subsequently, the cloud moves in the direction of the wind, resembling the flow of water, driven by the combined effects of wind force, gravitational settling, and its own momentum. As the movement of the dense gas cloud persists in the wind's direction, it mixes with the surrounding air, which dilutes and decreases its density. Once sufficiently diluted, the cloud eventually acts like a gas with neutral buoyancy.

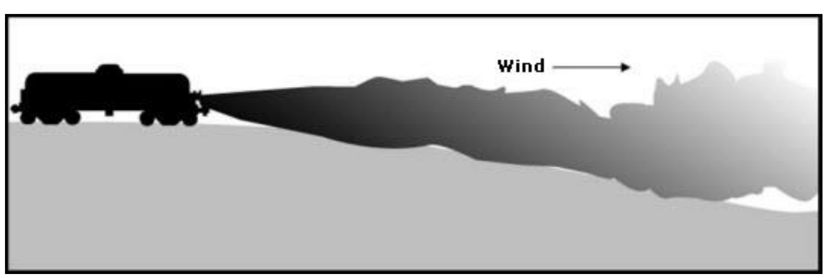


Figure 5-14. Illustration of heavy gas dispersion model [42].

The ALOHA software employs the BST approach to determine the overpressure caused by the ignition of flammable gases. This approach presupposes that the explosion originates within the zone where facilities handling combustible vapor are densely located. An integral aspect of the BST method is its capacity to modify the Mach number of the flame speed and the resulting overpressure in correlation with the obstacle density surrounding the point of ignition. For modifications of the flame speed, reference [51] contains a pertinent look-up table. Obstacle density is classified into three levels: high, medium, and low. In environments with a high concentration of physical barriers, highly reactive gases are prone a DDT transition. An example of atmospheric dispersion analysis using ALOHA is given in the next subsection.

5.5.3.2 Example: Syngas Dispersion Modeling in ALOHA

A dispersion analysis from a reference syngas production facility was studied [52]. Two syngas flows were selected as possible limiting safety cases owing to their high-mass flowrates. The first flow is the CO_2-rich syngas downstream of the RWGS reactor while the second flow is the post-selexol syngas that is further topped-up with hydrogen. The physical parameters of these flows are listed in Table 5-11 along with several safety density limits in parts per million (ppm). Protective action criteria (PAC) are concentration levels of chemical materials that threaten or endanger the health and safety of workers or the public. PACs is a collective term that includes acute exposure guideline levels, emergency response planning guidelines, and temporary emergency exposure limits values. Each chemical has its own PAC levels and there are three levels of PAC:

- PAC-1: Mild, transient health effects
- PAC-2: Irreversible or other serious health effects that could impair the ability to take protective action

PAC-3: Life-threatening health effects.

The maximum credible accident scenario is assumed as a complete rupture at either piping of these syngas flows. Dispersion of the first syngas leakage is modeled using the Gaussian dispersion model while dispersion of the second syngas leakage is modeled using the heavy gas model due to their physical properties.

Table 5-11. Syngas parameters.

Parameter	**Syngas #1**	**Syngas #2**
Temperature (°C)	63	211
Pressure (bar)	30	30
Mass flowrate (tons/hr)	214.1	76
Immediately dangerous to life (IDLH, ppm)	4,444.44	1,739.13
PAC-1 (ppm)	277.78	108.70
PAC-2 (ppm)	307.41	120.3
PAC-3 (ppm)	1,222.22	478.3
Emergency Response Planning Guidelines 1 (ERPG-1, ppm)	740.74	289.86
ERPG-2 (ppm)	1,296.30	507.25
ERPG-3 (ppm)	1,851.85	724.64
Lower explosive limit (LEL, %)	27.27	12.20
Upper explosive limit (UEL, %)	46.88	18.99

Two hypothetical reference NPP locations are chosen to demonstrate the proximity of the HTEF and the RWGS reactor to the NPPs. The first site is situated near a river, and the second is positioned in a desert region. A distinctive characteristic of the site by the river is its encirclement by a forest, which acts as a shield for the RWGS reactor, potentially limiting the spread of syngas by interfering with wind patterns, yet also potentially intensifying blast overpressure in the event of a syngas deflagration, as outlined by the BST method. Consequently, there is an interest in examining the dual effects of such an obstacle compared to the unobstructed desert site. Data on the 10-year wind rose graphs for these sites are depicted in Figure 5-15 sourced from the cli-MATE portal of the Midwestern Regional Climate Center [53]. Release scenarios of syngas are modeled in ALOHA for each wind direction to assess the impacts.

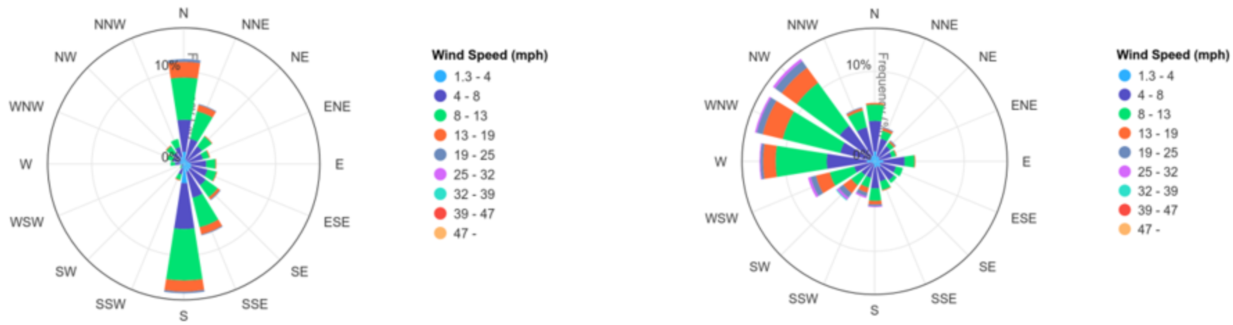


Figure 5-15. 10-year wind speed rose graphs for the reference riverside site (left) and the reference desert site (right).

ALOHA returns threat zone output results for toxic area of vapor clouds, flammable area of vapor clouds, and blast area of vapor cloud explosion for each wind direction. An example output plot is shown in Figure 5-16, where it shows the three PAC levels [54] of toxicity boundaries from a release of syngas flows with a 6.2 mph wind from the southwest direction. The top chart is for the first syngas flow modeled using the Gaussian dispersion model, and the bottom chart shows the heavy gas dispersion model for the post-selexol syngas flow. The differences in downwind range and area are likely caused by the extent of advection and the different PAC levels, since the heavy gas model travels closer to the ground and is therefore less affected by advection until it has diffused significantly to start behaving as a more buoyant gas.

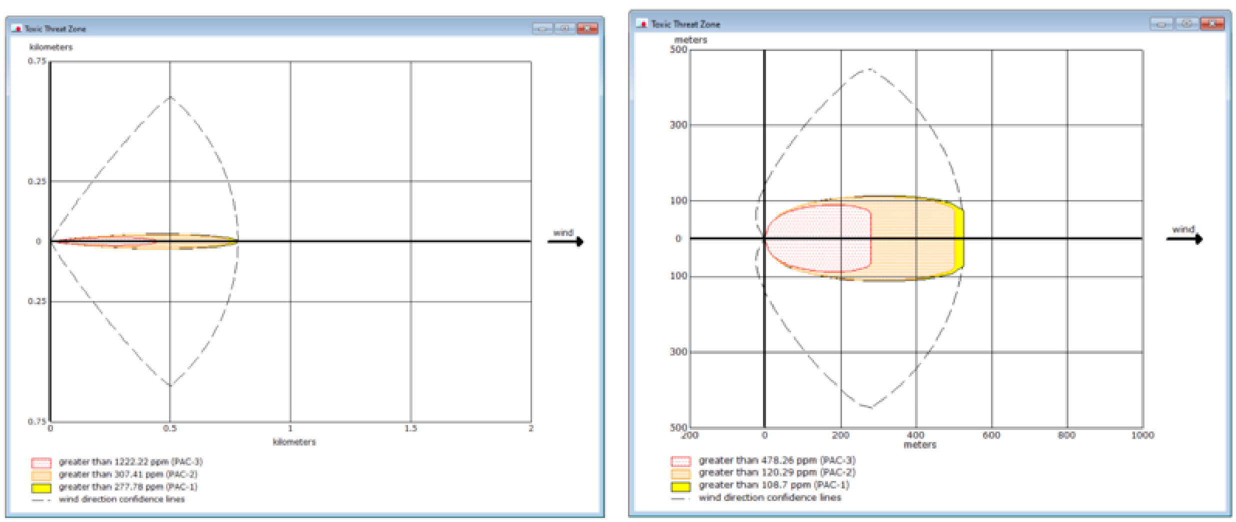


Figure 5-16. ALOHA output window showing syngas toxic areas for a given wind speed and direction, for the Gaussian dispersion model of flow #1 (left) and the heavy gas dispersion model of flow #2 (right)

ALOHA analysis was iterated for all average wind speed and directions in the wind-rose data to obtain toxicity and flammability level of concerns (LOCs) in all directions. The results are mapped in Figure 5-17 for the selected hypothetical sites. For both sites, the LOCs are plotted for the Gaussian dispersion model of flow because it exceeds the distance for the heavy gas dispersion model of flow (Figure 5-16). The figures show a 500 MW_{nom} HTEF located near a PWR. The minimum safe separation distances for hydrogen blast and heat flux damage to PWR SSCs are shown on the map. The figure also shows that toxicity LOCs extend farther than the syngas flammability/detonation LOCs represented by the solid colored lines extending from the syngas facility (blue rectangle). For the riverside site, the dense forest environment causes a “funneling” effect that compresses the ignition wave front such that the resulting overpressure reaches 1 psi from the ignition point. Meanwhile in the open desert site, the overpressure from syngas deflagration is less than 1 psi. Therefore, the LOC is plotted for the low explosive limit (LEL) instead of the 1 psi overpressure. In both cases, results suggest that the RWGS reactor should be placed at greater distance from the NPP relative to the HTEF distance to the NPP. Note however that these are hypothetical sites that do not correspond to any actual operating nuclear plant. Therefore, the results may vary when this methodology is implemented on an actual plant site. Nonetheless, this syngas case study serves as an example to illustrate hazard analysis for neutrally buoyant to heavier than air gases in an integrated energy system.

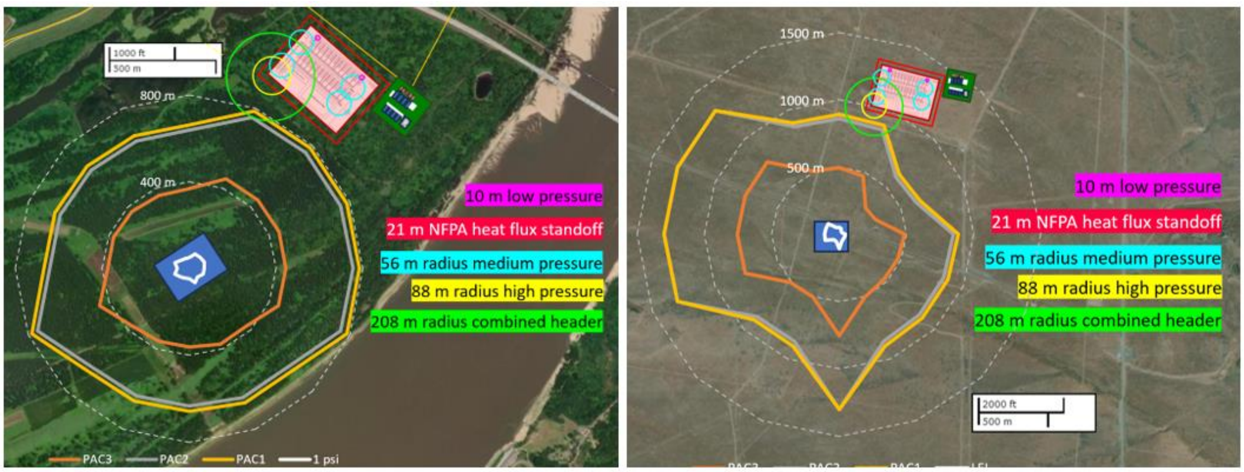


Figure 5-17. Distances at level of concerns for the hypothetical riverside (left) and desert (right) sites.

5.6 Analysis of Heat Flux from Fires and Fireballs

Another hazard arising from explosions is thermal heat flux radiated from fires. The hazards due to heat flux is both from the intensity and exposure time [38]. For that reason, the thermal hazards considered are usually from sustained fires which, in the case of combustible liquids and gases, involve pool fires, jet fires, and fireballs. We reported heat flux calculations from jet hydrogen fires within reference HTEF designs in our previous report [1]. The jet and pool fire scenarios for other industrial facilities are not repeated here because they require data on piping and combustibles flow (e.g., flow rate, pressure, temperature) which is not yet available at the initial research phase. However, an analysis of heat flux resulting from fireballs is presented as an example in this section.

A fireball may arise following a VCE, BLEVE, a boil over, or a pressure vessel burst. Fireball formation occurs as follows: depressurization of a pressurized hot liquid leads to partial flash vaporization and forms a two-phase liquid-vapor mixture. The resulting cloud burns at the edges because the interior concentration is above the flammability limits. Initially semi-spherical and close to the ground, the cloud becomes spherical and rises due to heat and turbulence, which also vaporizes the liquid droplets and reduces the cloud's density. Turbulence aids in efficient combustion, resulting in bright flames and high surface emissive power, allowing radiation to reach far distances. In summary, unique characteristics of fireballs compared to jet and pool fires are that fireballs lift off the ground, grow in size, and radiate an intense thermal flux.

The fireball analysis is selected as an example due to the unique characteristics described above. With its lift-off, its thermal radiation may be less attenuated by surrounding structures compared to ground fire, which may possibly lead to a higher radiation heat flux received by NPP SSCs as illustrated in Figure

5-18. The shortest distance between the center of fireball and the target is denoted as D/2+d, which gives the maximum radiation intensity to the target. Note that although it is called a fireball, it is not always shaped as a ball. Rapid tank failures create approximately spherical fireballs while slower BLEVEs typically create cylindrical fireballs. However, approximating the fireball volume as an equivalent sphere is found to be sufficient in predicting their thermal radiation effects [55].

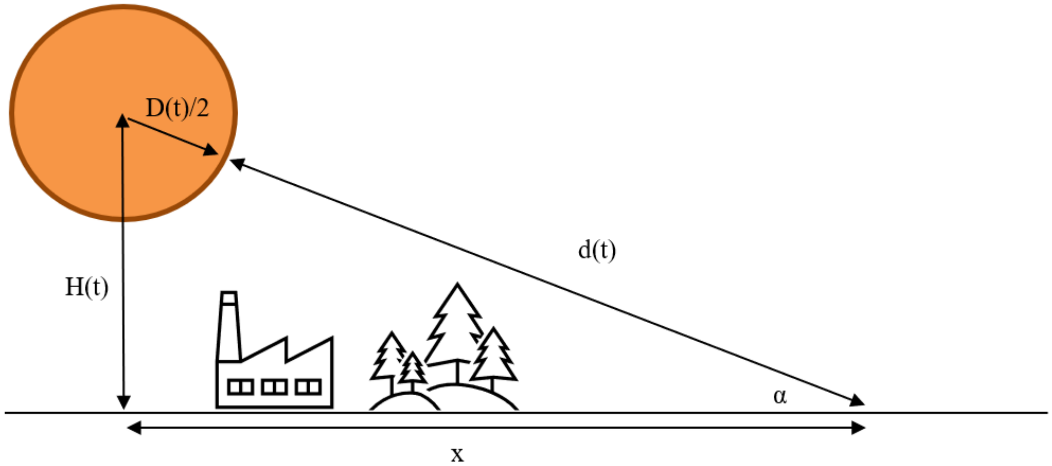


Figure 5-18. Geometry of a fireball and its distance to a target.

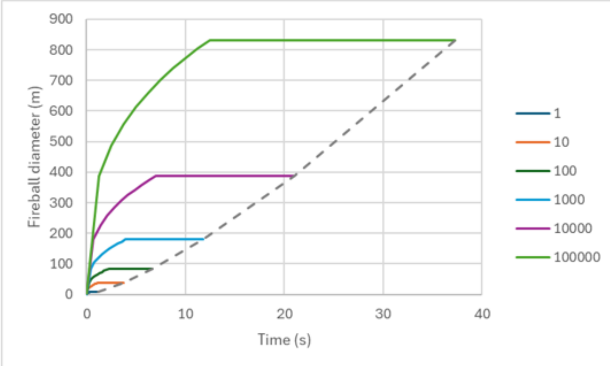
A fireball is assumed to form due to an explosion on one of the synfuel and refinery products listed in Table 5-12. It is assumed that there is no domino effect from the explosion. The method to calculate thermal radiation from a fireball is adopted from [35] for a range of products reacted from 1 gallon to 100,000 gallons. The steps to calculate radiative heat flux from a fireball are summarized as follows:

1. Assume the ambient pressure at the average atmospheric pressure of 101325 Pa, a relative humidity of 50%, and the ambient temperature at 20°C.
2. Calculate fireball's duration as a function of fuel mass, for a range from 1 gallon to 100,000 gallons.
3. Calculate fireball's diameter (D) and height (H) as a function of time.
4. Calculate the view factor (F), (i.e., the proportion of radiation that strikes the target's surface) as a function of fireball's diameter (D), height (H), and distance to target (d).
5. Calculate the atmospheric transmissivity (τ) to account for the atmospheric attenuation of the thermal radiation, as a function of time-varying distance between fireball and target (d).
6. Calculate the fireball's emissive power (E), which is the thermal radiation energy emitted omnidirectionally per unit area and time, as a function of time, assuming the radiant heat fraction (ηrad) is 1/3.
7. Calculate radiation heat flux for various targets from the initial detonation time until when fireball diminishes. The heat flux to population is multiplied by cosine α as shown in Figure 5-18, assuming most people are standing.
8. Calculate thermal dose by integrating the radiation heat flux over time numerically.
9. Apply the thermal dose to estimate health effects to population using Eisenberg's probit equations.

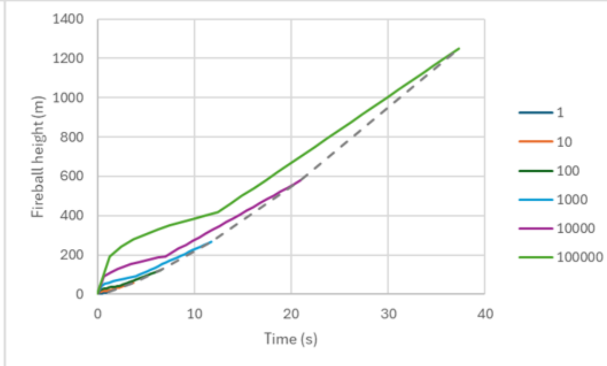
Table 5-12. Data of select synfuel products.

Product	**Density at 20°C (gr/cm^3)**	**Heat of Combustion (kJ/kg)**	**Reference**
Jet fuel A1 10264	0.78	43.2	[56]
Petroleum naphtha varnish makers & painters	0.75	42.4	[57]
Diesel	0.85	41.36	[58]
Methanol	0.79	19.58	[59]

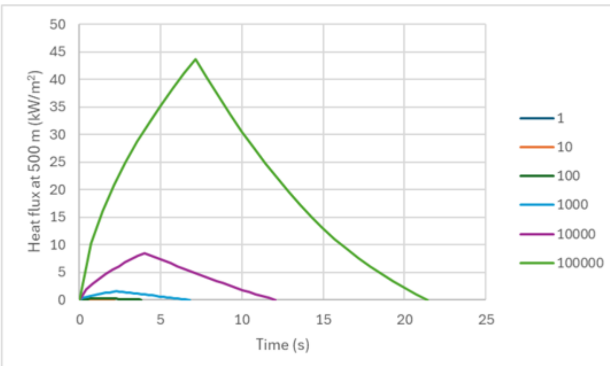
Results for the jet fuel fireballs are shown in Figure 5-19. As expected, the fireball's duration increases along with the amount of fuel combusted. Plot (a) shows fireball diameter that grows during the first third of its duration and remained constant afterward. Plot (b) shows the fireball's height which increases rapidly during the initial growth period. Both plots suggest the fireball's size and height increases exponentially with the mass of reacted fuel, which agrees with the power formula equation presented in [35]. To compare the heat flux evolution across various fuel masses, an arbitrary distance at 500 meters from the center of fireball was selected in plot (c). It shows the heat flux peaked at the first third of the fireball's duration, which increases exponentially with fuel's mass, then decayed steadily. Plot (d) shows the overall thermal dose throughout the fireball's duration at various separation distances, compared to the thermal dose that can damage equipment and structures of 35–37.5 kW/m^2 for 30 minutes [60] identified with a dashed red line where applicable. Finally, plots (e) and (f) show the first-degree burn and mortality of the surrounding population at various distances. Although the heat flux is not sufficient to damage structures, it may be harmful to offsite population including nuclear plant personnel who work outdoors such as maintenance crew and physical security guards, if a certain setback distance is not established.



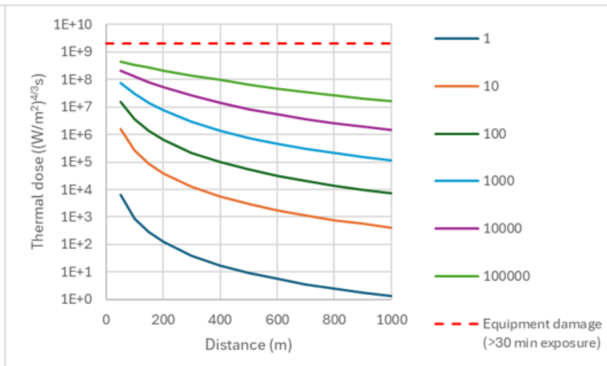
(a) Fireball diameter D



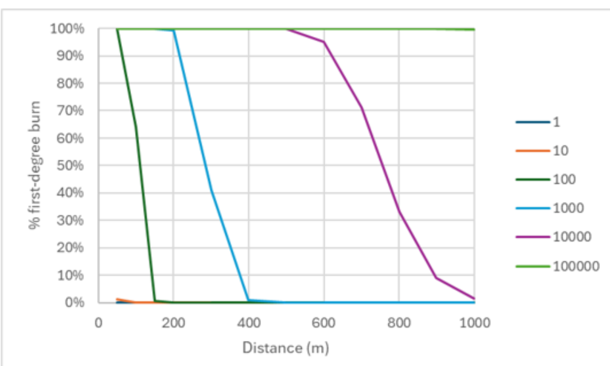
(b) Fireball height H



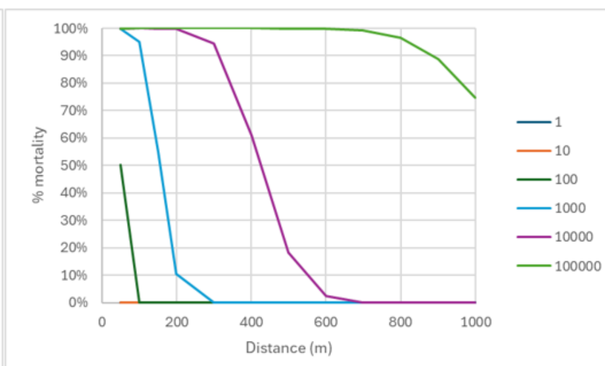
(c) Heat flux at 500 meters



(d) Total heat flux at various distances



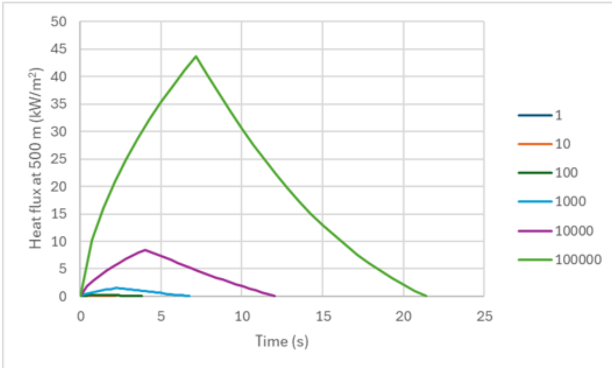
(e) Population % first-degree burn



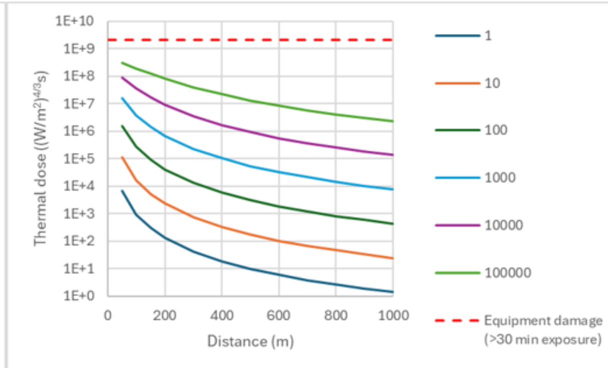
(f) Population % mortality

Figure 5-19. Comparison of fireballs resulting from the combustion of 1 gallon to 100,000 gallons of jet fuel.

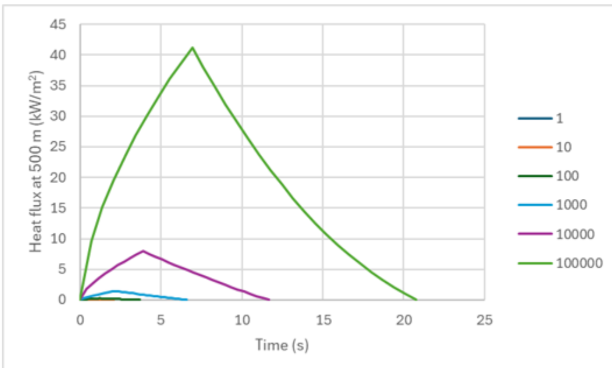
Figure 5-20 compares the heat fluxes and thermal dose from various synfuel products fireballs, where the heat flux comparison was done at the median of the distance evaluated (i.e., at 500 meters). The figure shows that diesel and naphtha fireballs generate similar outputs of heat flux and thermal dose, meanwhile methanol generate the least thermal output. All three products create less thermal output compared to jet fuel. None of the fireballs radiate heat that can damage nuclear plant SSCs, although a setback distance still needs to be maintained for nuclear plant personnel's safety.



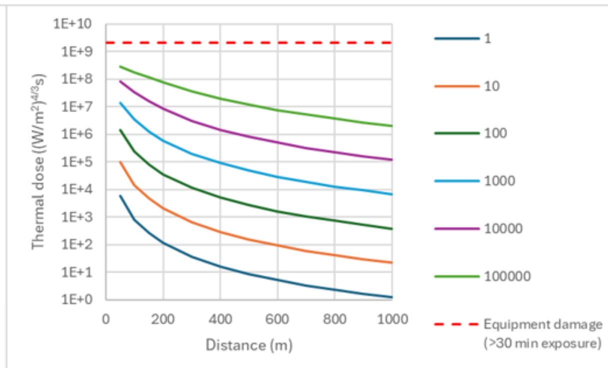
(a) Heat flux from diesel fireballs



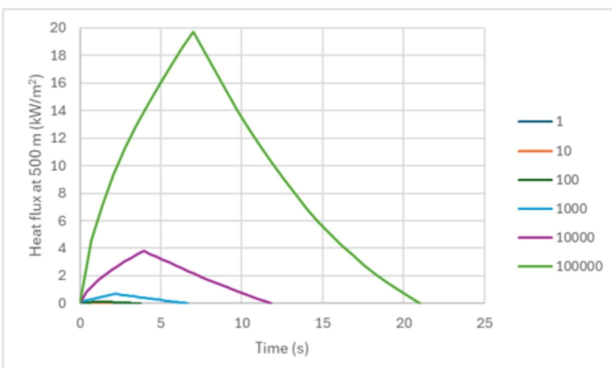
(b) Thermal dose from diesel fireballs



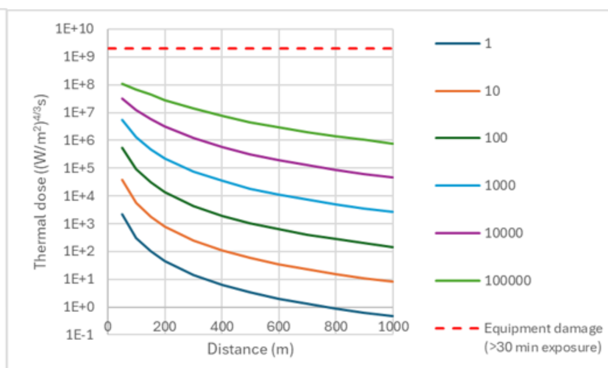
(c) Heat flux from naphtha fireballs



(d) Thermal dose from naphtha fireballs



(e) Heat flux from methanol fireballs



(f) Thermal dose from methanol fireballs

Figure 5-20. Heat flux from various synfuel product fireballs.

5.7 General Plant Transient Due to Overcurrent from Electrical Transmission

The addition of the HES to the NPP requires a direct electrical connection between the NPP and the industrial customer. The design of this connection is described in Section 4.2 and illustrated in Figure 4-4. Most notably, the main turbine generator of the NPP is directly linked to the industrial customer to provide electricity. If there is an overcurrent event at the industrial customer or generator transformer, it could damage the turbine generator if the protections such as circuit breakers fail to isolate the generator.

The turbine generator could also be damaged if the circuit breakers and relay protections fail spuriously and remove the pathway for the load to be dumped.

These protections could also fail if they were to fail due to a seismic event. These seismic considerations were made. The PRA logic includes options for seismic events in five bins ranging from a peak ground acceleration of 0.17 g to 2.12 g. Bin frequencies and gamma uncertainty distribution parameters utilized are from the NRC generic BWR and PWR models. These are reported in Table 5-13.

Extensive searches on seismic fragility constants were performed, and it was not possible to find seismic fragility data for components at as high a level as designed for this transmission system. The fragility constants for the highest voltage components available were used and are reported in Table 5-14. This only records the data used for relays, busbars, and switchgears. The data provided for the busbar was not individual βr and βu but an overall βc [61]. The best data available for circuit breakers and transformers were found in a report that did not explicitly provide fragility constants but provided a fragility curve instead [62]. Values at the seismic bins utilized in this model (Table 5-13) were extracted from the curve and are reported in Table 5-14. It was not possible to find seismic fragility data for components at as high a level as designed for this transmission system, but the data for the highest voltage components available was used.

Table 5-13. Extracted probabilities for high-voltage circuit breakers and transformers [62].

Seismic Bin #	PGA (g)	Probability	
		Circuit Breaker	Transformer
1	0.17	0.020	0.020
2	0.39	0.380	0.380
3	0.71	0.827	0.806
4	1.22	1	0.972
5	2.12	1	1

Table 5-14. Seismic fragility constants used for high-voltage relays, busbars, and switchgear.

Component Type	Fragility Constants		
	Am (g)	βr	βu
Relay [62]	0.9	0.35	0.37
Busbar [61]	1.476	βc = 0.438	
Switchgear [62]	1.5	0.32	0.48

5.8 Control Room Habitability

The control room habitability analysis was performed based on the methodology proposed by Ref. [63]. Equation (10) shows the control room transient hazardous gas concentration evolves with time used in Ref. [63].

$$C = C_i(1 - e^{-\frac{V_i}{V}t}) \qquad (10)$$

- C_i: Control room hazardous gas intake concentration
- V_i: Control room heating/ventilating/air conditioning (HVAC) intake flow rate (ft^3/minute)
- V: Control room volume (ft^3)

Equation (10) has two fundamental assumptions:

1. The hazardous gas can only travel through the HVAC system from outer area of the building to the control room.
2. C_i is independent of time. That is, the hazardous gas concentration does not change with time.

For demonstration of this methodology in the co-located industrial facilities, Syngas would be used and the concentration intake reported in Table 5-11 will be used. Specifically, it is assumed that PAC-1, PAC-2, or PAC-3 reaches the intake of HVAC system. The control room intake flow rate and the control room volume are shown in Table 5-15.

Table 5-15. Properties of control room air flow.

Parameters	**Values**	**References**
V_i	2,220 ft^3/minute	[63]
V	50,554 ft^3	[63]

Figure 5-21 shows the results of the transient syngas concentration in a control room. It took approximately 120 minutes to reach the maximum concentration. However, due to the fact that the PAC-1, PAC-2, and PAC-3 are all smaller than the IDLH, there is limited concern for operators if the simulated concentration is reached.

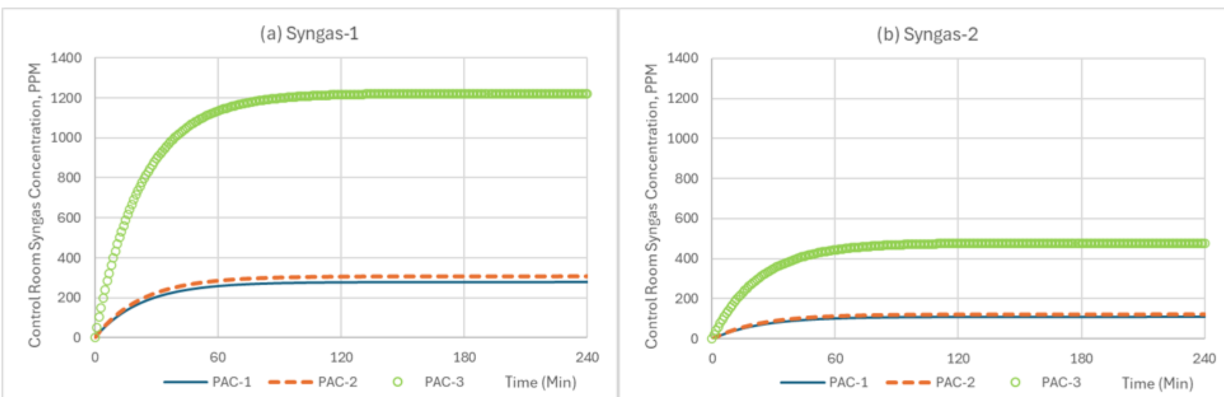


Figure 5-21. Transient syngas concentration in the control room of a nuclear power plant.

Depending on the time last for the transient event, the concentration can be different. Based on the results from Figure 5-21, the maximum concentration can be reached within 2 hours for Syngas-1 and Syngas-2. Syngas-1 has higher PAC-3 concentration compared to Syngas-2. Therefore, 30 minutes, 60 minutes, and 120 minutes of the transient time are used to compare the evolution of the control room syngas concentration as shown in Figure 5-22.

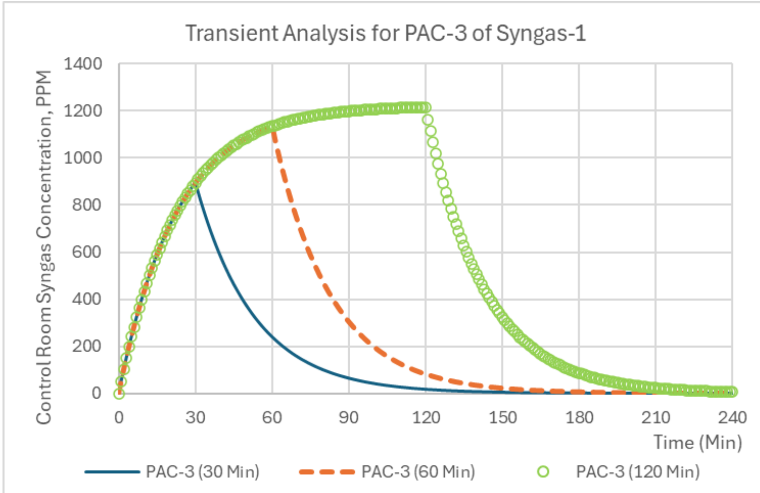


Figure 5-22. Transient syngas concentration in the control room of a nuclear power plant.

In Figure 5-22, it is observed that the earlier the transient can be stopped, the earlier the concentration of the hazardous gas can be restored to the normal value. Note that this analysis does not fully incorporate the ALOHA transient analysis. It was assumed that the leakage of the syngas can be quickly terminated from methanol plant once an accident happened. A full scope of the analysis can be done by integrating the transient analysis from ALOHA starting from the gas leakage in the nearby facility and use the calculated concentration in a shortest distance nearby the HVAC system.

6. PROBABILISTIC RISK ASSESSMENT MODEL

Many of the basic designs of ANPPs were developed at national laboratories and universities around the same time as the LWRs and continued through the years. Unfortunately, not many PRAs from this early development were made publicly available. Those that are publicly available exist on paper alone, the software models are lost to time and the improvements in technology. The series of reports evaluating the safety effects of modifications required of LWR NPPs that use generic, publicly available PRAs has proved invaluable, and it is desired to have the same capability for ANPPs going forward. The first ANPP that is modeled is a high temperature gas reactor (HTGR) developed in the 1980’s. It is summarized in the following paragraphs, is validated to match the original model’s results and will be publicly available at INL and university repositories.

6.1 Modular High Temperature Gas-Cooled Reactor Model

A PRA model of a modular high temperature gas-cooled reactor (MHTGR) was built and validated using a publication from General Atomics (GA) [64]. The innovative configuration of the MHTGR is engineered to depend minimally on active safety mechanisms. Instead, the reactor's core size, its geometric design, and the chosen power density are strategically determined to enable the decay heat to dissipate from the core through natural processes of radiation and conduction alone. Consequently, this design ensures that even in the event of a total loss of primary coolant, the core effectively contains radionuclides, preventing their significant release [65]. Many of these concepts are used in modern HTGR designs.

A detailed supporting document is being written which will include all underlying assumptions, provide an exhaustive analysis of the new model, and cover the validation of the new model.

This report provides an overview of the MHTGR, the PRA model, and the validation process of that model using the GA documented model.

The MHTGR design features a plant with four reactor modules, each coupled in parallel to a pair of turbine generators. Each module has a nominal thermal power rating of 350 MW_t and an electrical power rating of 140 MW_e. The primary coolant is helium and operates at a pressure of 6.38 MPa when discharged from the circulator at rated power. The estimated helium temperatures are 258 °C upon core entry and 687 °C upon core exit. Key components of each module include a prismatic hex-block reactor core housing TRISO fuel with uranium oxycarbide as the fissile material, a steam generator, a helium circulator, a shutdown heat exchanger, and control rods.

Although there has been previous development of PRAs for the MHTGR, a gap remains due to the absence of updated computer-based PRA models. The event and failure data foundational to these assessments are now recognized as outdated. The goal was to leverage the existing PRA model documentation to establish a validated, computer-based MHTGR PRA model. This model will then be updated with modern data and design features. Employing generic ANPP PRAs is essential for research to assuage proprietary concerns and to ensure the general ANPP reactor type's safety is thoroughly assessed with the latest information. The interest in the MHTGR is attributable to its similarity to current HTGR designs and its potential for integrating thermal and electrical energy production to an industrial facility [66].

The original GA model ETs and FTs were quantified as radionuclide release category frequencies. Final mean release frequencies were tabulated, and these values were used as a validation metric for the computer-based model. The release frequencies were based on the entirety of the plant and the use of a four module, two turbine system.

The GA model was translated into a Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) software model. SAPHIRE is an INL developed PRA software developed for the NRC, used primarily for existing nuclear power plants.

6.1.1 Basic MHTGR Model Introduction

A complete description of the model SAPHIRE model will be included in a separate report that is currently in work. A brief introduction is provided here.

The SAPHIRE model includes the FTs as presented by the GA publication. However, GA does not include the use of the common cause failure events within the FTs themselves; GA calculated these values separately and did later addition, as was the state of practice in 1987. SAPHIRE is able to calculate common cause failures within the fault tree analysis, so where applicable, common failure events were added using β factor events. The β factor values were tabulated within the GA appendices, and these values were used within the SAPHIRE model. FTs were compared to system diagrams to ensure proper gate logic. Disagreements between GA's model and system diagrams will be noted in the supporting validation document and will be addressed in future updates to the SAPHIRE model. Top event FTs used in the quantification of the ETs include the failure of the heat transport system (HTS) in at least one module, failure of the shutdown cooling system (SCS) when one module requires cooling, and the failure of the intentional depressurization of primary coolant.

The probability of failure for the HTS (Figure 6-1) considers all four reactor modules. This fact is evident in the plant protection instrumentation system (PPIS) trip. Each module is prescribed an independent PPIS, and a failure in any of the systems endangers at least a single reactor module. The nuclear steam supply system (NSSS) is also an example of failures affecting a single module. A failure of the primary coolant circulator may endanger a single module, but common cause failure between the circulators of each module is also considered here.

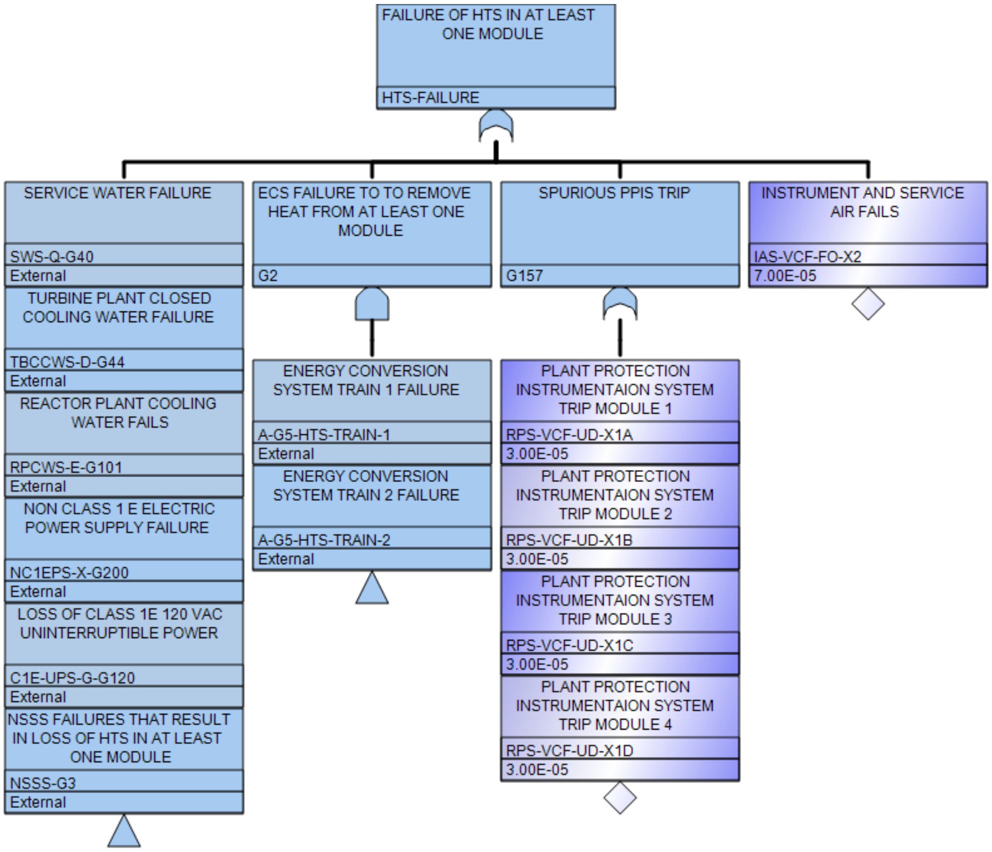


Figure 6-1. FT of HTS failure in at least one module.

The failure of the shutdown cooling system (Figure 6-2) is evaluated on the basis of a single module requiring cooling. Given the HTS is unavailable, the SCS provides a secondary means of forced circulation by transferring the residual heat to the service water subsystem.

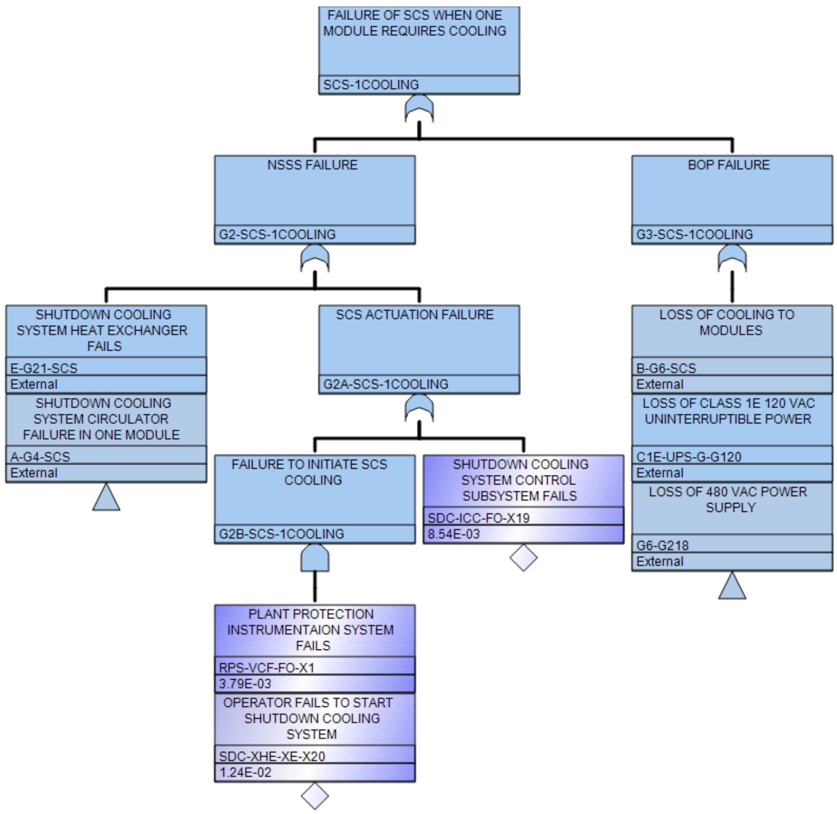


Figure 6-2. FT of the failure of the SCS when one module requires cooling.

Intentional depressurization of the primary coolant (Figure 6-3), also referred to as coolant pump down, is of concern when regarding release of radionuclides. A significant portion of radionuclide release involves the escape of primary coolant into the containment building. Given the primary coolant has contact with the fuel, some activity circulation is guaranteed.

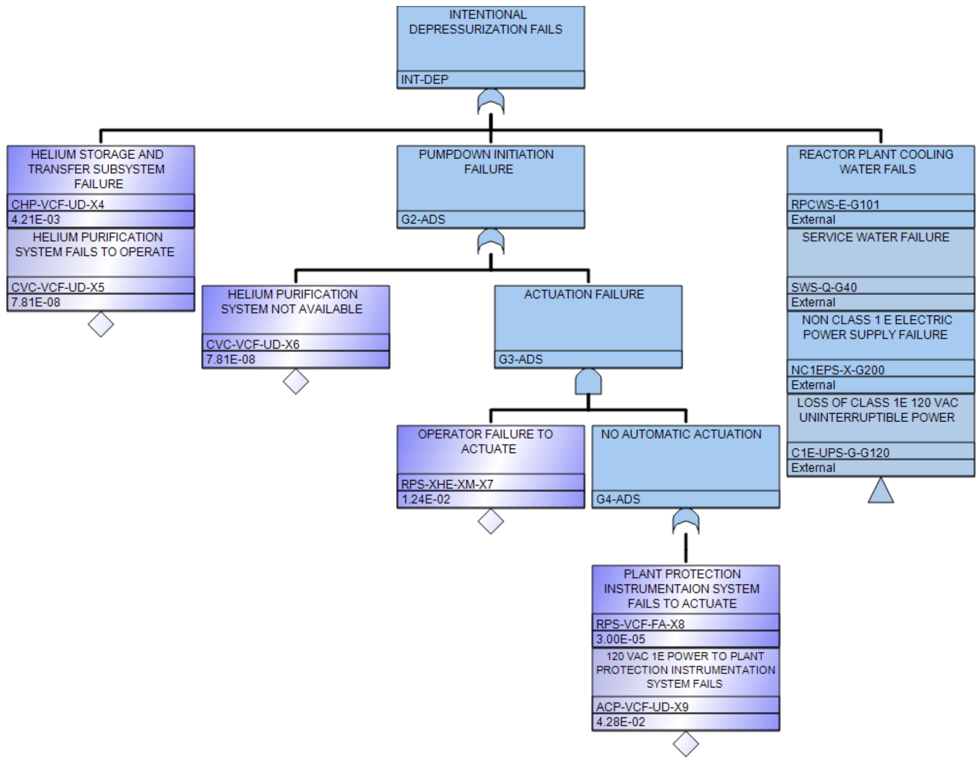


Figure 6-3. FT of the failure to intentionally depressurize the primary coolant.

Basic event data was selected from tables included in GA's analysis as well as their cited sources. This was done to ensure proper validation and non-addition of current data. GA did not quantify ET logic by simply assuming independence between each event, and uncertainty within the analysis required quantification. GA's publication also does not use simple point values, and repair times were included. Within the SAPHIRE model, care was taken to match appropriate mission times, repair times, and uncertainties using primarily lognormal distributions with error factors of 10.

6.1.1.1 Overview of Initiating Events in MHTGR

Seven initiating events were selected and validated during the process to identify the potentially most dominant contributors to plant safety; these include primary coolant leaks, loss of the main cooling loop, seismic activity, loss of offsite power and inadvertent turbine trip, anticipated transients requiring reactor scram, control rod group withdrawal, and steam generator leaks. Based upon a cutoff value of 1E-8, primary coolant leaks, loss of the main cooling loop, anticipated transients requiring reactor scram, and steam generator leaks were evaluated to result in potential release of radionuclide material. The ETs used within the SAPHIRE model are presented in Appendix A.

It is noted, seismic activity was modeled within SAPHIRE, but it is not currently validated. The logic and basic event data is included, but ground movement and seismic intensity have not been evaluated.

In the GA model, a loss of offsite power was not evaluated to result in the release of radionuclides, even with median frequencies above the cutoff value. Given a loss of offsite power and a loss of the backup shutdown cooling system, the passive nature of the reactor core cooling system allows the reactor module to release heat through radiation and conduction alone. Relying on the statement from GA, “the fuel type and enrichment have been selected so as to favor an intrinsically strong negative temperature coefficient, thus the reactor tends to inherently shut itself down in the event of undercooling or overpower transients.” Given there is not a leak allowing coolant release, the closed nature of the MHTGR means there is extremely low risk of radionuclide release given the loss of offsite power and loss of both turbines. This may be investigated further in future work.

Like the loss of offsite power, the inadvertent control rod group withdrawal was not evaluated to release radionuclides. The low-density fuel of the MHTGR is estimated to only undergo a few hundred degrees of temperature rise before the negative temperature coefficient halts the event. GA states, “the negative temperature coefficient terminates the event even for step reactivity insertions as large as the control rod pair which might be considered.” The success of control rod insertion is considered highly reliable, due to the redundancy in the plant protection instrumentation system, but in the event of failure, the design of the MHTGR greatly limits the potential risk of material release. Again, this may be investigated further in future work.

Primary coolant leakage has been identified as a possible contributor to radionuclide release across all evaluated end states. The interaction of the primary coolant with the fuel facilitates some degree of activity circulation. Moreover, the leak size determines the degree of impact on the cooling equipment and the potential for graphite oxidation. Specifically, leak sizes exceeding one square inch are critical because they overwhelm the helium purification system's capacity to reduce pressure and transfer the gas to storage tanks promptly. Larger breaches, such as a guillotine rupture, are accounted for with leak sizes over 13 square inches. However, the frequency of such extensive breaks was calculated to fall below the cutoff value, deeming them highly unlikely to occur.

In scenarios involving the loss of the main cooling system, only a single end state was found to exceed the cutoff criteria with the potential for radionuclide release. This scenario begins with a reactor trip, followed by a failure in the shutdown cooling system. Subsequently, if the passive reactor cavity cooling system (RCCS) also fails and the helium pump down is successful, but vessel cooling is not restored before core damage occurs, there is a potential for release. The likelihood of this sequence culminating in radionuclide release was estimated at 2E-8 per plant year. In the absence of any effective cooling over a prolonged period, the reactor vessel is expected to fail, leading to the release of material.

Anticipated transient without scram also produces a single evaluated end state with potential release, under cutoff. The progression is the same as described for the loss of main cooling, and it was evaluated to have the same frequency.

Steam generator leakage into the primary coolant is addressed by two distinct ETs, categorizing leaks as either small or moderate. In the context of the MHTGR, water ingress presents three principal concerns: the release of primary coolant through relief valve venting, the potential for fuel hydrolysis, and the resultant reactivity effects on the core. The assessment suggests that the most probable outcome following water ingress is an end state without a significant dose received. It is only when additional safety measures fail that the likelihood of radionuclide release increases. Release should be averted if over-pressurization is mitigated and the primary relief system functions correctly. However, scenarios involving compromised cooling or an inability to isolate the steam generator can lead to over-pressurization and the actuation of the relief valve. The duration of venting through the relief valve is a critical factor in determining the extent of radionuclide release.

GA’s assessment of the MHTGR PRA is primarily focused on the release of radionuclides and dosage, and it is generally in agreement with current non-light water reactor PRA standards written many years later that concentrate on release categories and not overly simplified core damage frequency. If core damage frequency is desired, the MHTGR PRA can be assessed back to a traditional LWR level 1 PRA. For example, given a steam generator leak, no release of radionuclides is predicted if the primary relief train response does not include venting, but fuel damage may have still occurred. Moisture causing hydrolysis of failed fuel and the oxidation of graphite may weaken the core. Water acts as a moderator of fuel, thus potentially increasing the temperature of the core, making it more difficult to cool. Increased temperature, pressure, and weakening of the core is viable to be considered as addition to the core damage frequency. The frequency of this sequence is assessed to be 1E-3 or one in 1,000 reactor operating years. Review of GA's ET frequencies and those verified within the SAPHIRE model suggests that core damage frequency is greater than that of radionuclide release frequencies.

6.1.2 Validation of the MHTGR SAPHIRE Model

What follows is a synopsis of the validation process and the methodology applied to the generic MHTGR PRA.

The validation of the MHTGR SAPHIRE model began with the validation of GA's ETs and event data followed by the verification and quantification using ETs. The validation criterion was based on an absolute percent difference between GA's tabulated frequencies of release categories and the mean frequencies calculated by SAPHIRE, with a threshold for success set at under 15%. Equation (11) presents the formula used for this comparison.

$$\left|\frac{A-B}{\left(\frac{A+B}{2}\right)}\right| * 100\% \qquad (11)$$

Where A represents the GA model's tabulated value and B is the SAPHIRE-calculated frequency.

The tabulated data presented by GA includes only those end states in which there is a release of radionuclides. End states that did not end in a form of release were prescribed an end state of 'NONE' and discarded. For end states which shared a release category, GA used an unbiased estimate of the true mean using Equation (12).

$$\bar{y} = \frac{\sum_{i=1}^{N} y_1}{N} \qquad (11)$$

Where y is the outcome of a sample and N is the number of samples.

ET validation was performed using two separate methodologies. Initially, the focus was on the sequence logic of the ETs. Given the complexity and multiple end states in many ETs, accurate branching validation was critical for precise calculations. These trees often featured top events with non-binary outcomes, such as the leak size distribution in the primary coolant leak ET, which includes a spectrum of possible leak sizes impacting various components. These leak sizes were categorized into five groups within a single top event. To ensure fidelity, this complex structure was replicated in SAPHIRE.

The first method of ET validation began with the calculation of end states using the nodal probabilities as presented by GA. These calculations did not include uncertainties, so the final end states were simply the multiplication of end state pathways. Within SAPHIRE, the top events were replaced with validation FTs that mirrored the nodal probabilities of the published models. The SAPHIRE model was then quantified for each end state and compared against GA's values using equation (11). Using this method, the average percent difference was nearly zero, suggesting correct ET sequence logic.

Following the successful validation of the ET logic, the provisional FTs used for validation were replaced by the actual FTs and corresponding basic event data. GA's analysis provided a table categorizing mean release frequencies along with the dominant sequences for each category. The second method of ET validation involved aligning the SAPHIRE-built FTs with the top events to these mean frequencies as reported by GA. This alignment was achieved by quantifying the ETs in SAPHIRE and conducting an uncertainty analysis on the resulting end states. Results from SAPHIRE were then compared to GA's using Equation (11) to calculate the absolute percent difference. The validation was deemed successful when the difference was under the 15% threshold. All quantified end states met this success criterion, and the dominant sequences were accurately reflected. A comprehensive list of the encountered challenges, the assumptions made, and any deviations from the original model will be documented in the supporting validation document.

After concluding the second method of ET validation, it was inferred that the FT logic was sound, and that the incorporation of basic event data was accurate. GA's publication does not provide explicit probabilities for the basic events within the FTs, instead referencing an internal appendix and additional sources for their selection. Meticulous effort was made to apply the basic event probabilities as they were presumably utilized by GA. Nevertheless, certain FTs or pathways may have a negligible impact on the overall top event probabilities, raising the possibility that an incorrect basic event probability could be applied without significantly altering the outcome. To mitigate this risk, a thorough review of the FTs and a well-documented rationale for all basic event data selections were carried out.

6.1.3 MHTGR Linkage to an Industrial Facility

The integration of an HTGR with an industrial facility garners interest due to the reactor's modular nature, capability to produce high-temperature steam, and provision of electrical power. However, the design and placement of the reactor near the industrial customer are affected by the hazards documented throughout this report.

HTGR designs such as the MHTGR mitigate some of these risks by situating the reactor vessel and steam generator below the grade level of the surrounding floor, offering enhanced protection against external events, effectively providing an engineered barrier.

The MHTGR does rely on offsite power. In the event of a LOOP, the MHTGR is equipped with backup generators to restore power to the shutdown cooling system, but lack of power does not affect the ability of the RCCS to passively remove decay heat. So, with a loss of offsite power, there would likely be an increase in fuel damage, but it may be less than the given cutoff.

The primary concern centers around impairment or obstruction of the RCCS. The RCCS is anchored to the reactor building. The reactor building would have to sustain substantial damage or collapse to compromise the RCCS. In such an event, where all cooling is lost, core temperatures could potentially reach upwards of 1870 °C, leading to vessel failure. Obstruction of the airflow is a more likely event, however, the likelihood of losing the RCCS is deemed low.

Frequencies calculated within the validation of the SAPHIRE model may not reflect current estimates because the basic event data was used from the 1987 model to validate this model. Updated data will be used in the model for future work.

Other future work will include modeling the heat extraction system and electrical connection from the MHTGR to the industrial customer.

7. LICENSING PATHWAY SUPPORT FROM THIS DOCUMENT

The NRC uses Codes of Federal Regulations and develops various regulatory guides to conduct a safety review of the proposed NPP. The primary Code of Federal Regulation used is 10 CFR Part 50 Domestic Licensing of Production and Utilization Facilities [67]. The primary safety documentation provided to the NRC for a site operating license is the final safety analysis report (FSAR). The FSAR is populated with deterministic safety assessments and a description of the design-specific PRA and its results.

The contents of this report include supporting deterministic and probabilistic analyses that can be useful in preparing an FSAR for a site operating license application that includes co-located industrial facilities.

7.1 Adherence to the Site Fire Protection Plan

The placement of an industrial facility within the OCA of the existing NPP site will be within the NRC's regulatory jurisdiction. This means that, among other things, the safe siting separation distance will be dictated by the site's fire protection program/plan (FPP). As of the publication of this report there are only hydrogen facilities proposed for placement within the OCA. A report on code and licensing separation distance considerations [68], prepared concurrently with this report, covers FPP adherence for a hydrogen facility co-located with an NPP.

All sites have the FPP within the final safety analysis report and each site uses a plan agreed to with the NRC for their license. This can include a deterministic approach through 10 CFR 50 Appendix R and/or a risk-informed approach through 10 CFR 50.48(c) [69]. The risk-informed approach is also known as "NFPA-805 plants" which is the NFPA code called out within the 10 CFR 50.48.

Independent of the FPP classification, the first step in self-evaluating a co-located industrial facility is to clearly define the addition to the site OCA and conduct an impact review. If 10 CFR 50.48(c) is followed, a preliminary risk screen is performed to evaluate if the impact is potentially more than minimal. The results of this screen determine if a qualitative risk evaluation is sufficient, or a more detailed quantitative evaluation is necessary. Once the risk evaluation is completed, the results are compared against the delta frequency and consequences in the PRA. Assuming the risk acceptance criteria are met, safe separation distance is determined by strategies such as detailed in Section 5.5.

More likely, an HTEF or other industrial facility located in an NPP OCA today would be designed to NFPA 2 [18]. As described within NFPA 2, the intent "shall be to provide fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas (GH2) form or cryogenic liquid (LH2) form." Thus, the general associated piping and equipment and other code safety standards to be employed for the HTEF as a stand-alone compressed hydrogen gas facility in the NPP OCA currently would be expected to meet NFPA 2 although this code is not directly referenced within the licensing pedigree of NFPA 805 plants. Employing this widely accepted code standard would however be wisely included as a design evaluation basis provided under the fire protection engineering evaluation.

More information can be found in Ref. [68], however the focus of that document is on revisions of existing NPPs. Both the heat flux methodology and criterion of 37.5 kW/m^2 for a 30 minute duration and the blast overpressure methodology and criterion limit of $\leq$1.0 psi set forth in this report provide conservative safe separation distances when compared to any of the codes and regulations listed in this section.

7.2 Licensing Support through RG 1.91

RG 1.91 [3] is the current NRC Regulation Guide for evaluating explosion risks near an NPP, meaning outside of the OCA. Some existing NPPs have used RG 1.91 analyses in their safety case. The TNT mass equivalent methodology is used, and standoff distances are required to limit a maximum credible accident to less than a 1 psi overpressure. We recommend, along with reference [68], that license applicants use the RG 1.91 methodology and criteria with a maximum break-type leak as a bounding overpressure effects tool for establishing a safe separation distance between the industrial facility and the NPP SSCs to provide a conservative assessment of safe separation distance when compared to NFPA minimum standards. The NFPA standards allow lesser experientially-based leakage sizes, but the decrease in safe siting distance is generally not advantageous given typical NPP site configurations and the longer distances inherent between NPP SSC's and logical siting locations within or outside of the OCA.

8. CONCLUSIONS

Generic specifications of industrial customers were used in this report and some processes to produce carbon-reduced fuels were used in the pre-conceptual design stage. The reference facilities were a methanol plant, a syngas production, an oil refinery, and a wood pulp and paper mill. Hazards were identified and assessed for potential consequences through accidentology and FMEAs. The safety of the ANPP was the primary focus of this research; however, FMEAs were expanded to include informational results for the industrial facilities, public safety and perception, and economic concerns. Methodologies were presented for determining safe separation distances from these potential hazards that ensured the safety of the NPP, workers, and the public. Probabilistic risk results were presented for the changes required of the NPP to support industrial customers.

It is important to eliminate, through distance and/or mitigation, the external hazards presented by the reference industrial facilities through safe separation distance of the facility to the nearest NPP SSC. Deterministic analyses, approaches, and considerations presented in this report can be used as a part of an overall strategy to define this safe separation distance between the point of hazards presented by the industrial customer to the nearest NPP SSC. This safe separation distance is used to meet FPP criteria set forth in NFPA standards, U.S. Codes of Federal Regulations, and regulation guidance that the NRC uses to license NPPs. Engineered safety barriers can also be credited while following safety codes and regulations. Beyond licensing requirements for NPP safety, the report's example deterministic analyses provide tools to evaluate the safety of workers and the public near industrial facilities in case of fire, detonation, and toxicity.

A public-use MHTGR PRA was modeled and validated to perform future assessments on the required additions to the ANPP for the thermal extraction systems and direct electrical connection to the industrial customer.

The hazards analyses and MHTGR PRA creation presented in this report provide a toolbox and starting point for site-specific assessments that can be used to ensure the safety of the ANPP, the industrial facility for some discrete failures, and the public and to help meet regulatory licensing criteria to co-locate an industrial facility near an ANPP. No attempt was made to meet any federal regulatory requirements or safety standards, or to assess all hazards present for the industrial facilities themselves beyond the assessment of hazards identified as potential threats to NPP safety.

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Appendix A MHTGR PRA Model

This appendix shows the MHTGR ETs used in the validation of a SAPHIRE PRA model. Seven initiating events are described in the body of this report, but eight event trees are listed. The initiating event of a steam generator leak is given by two event trees denoting either a small or moderate size leak.

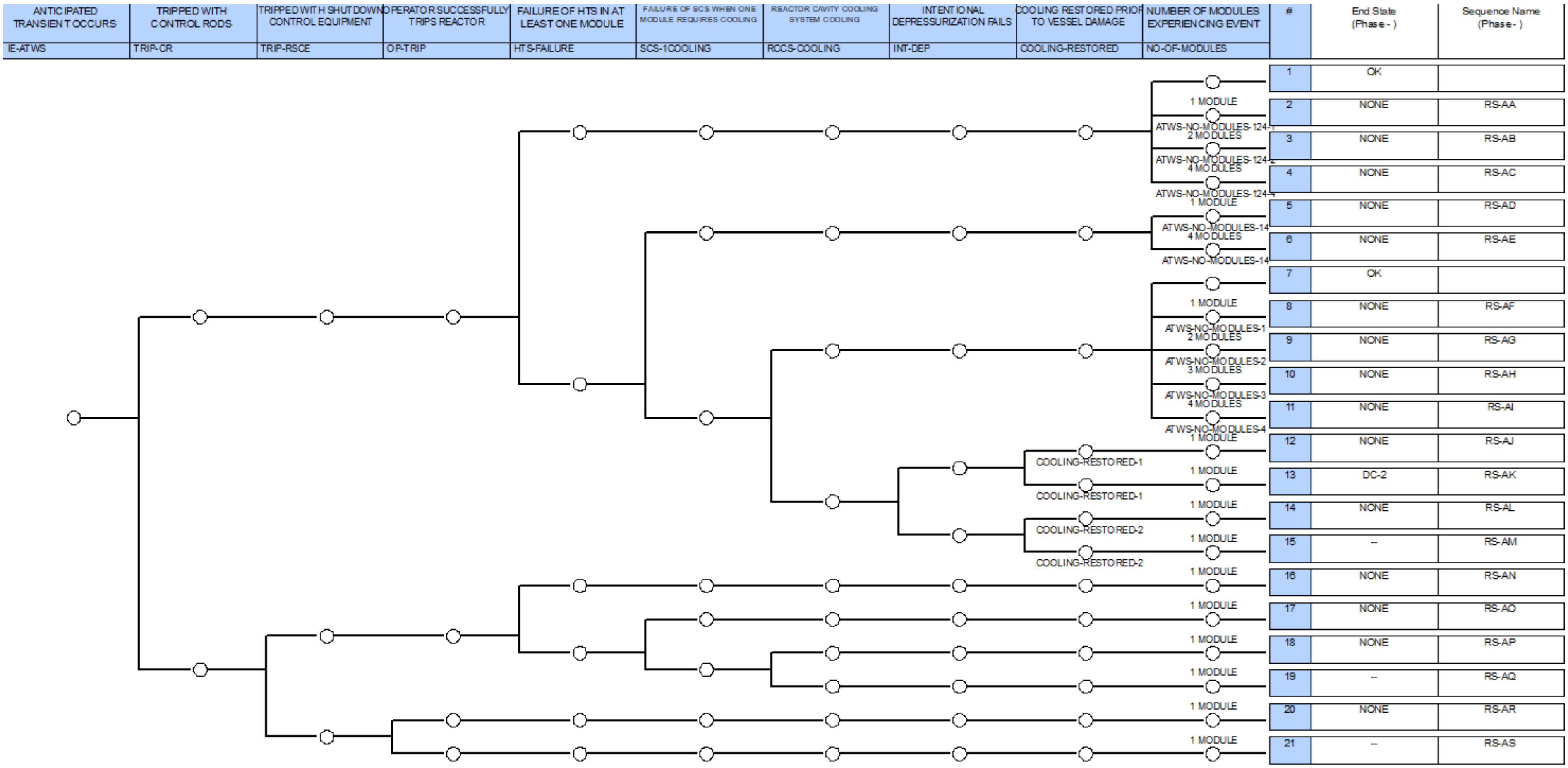

Figure A-1. Anticipated transient without scram.

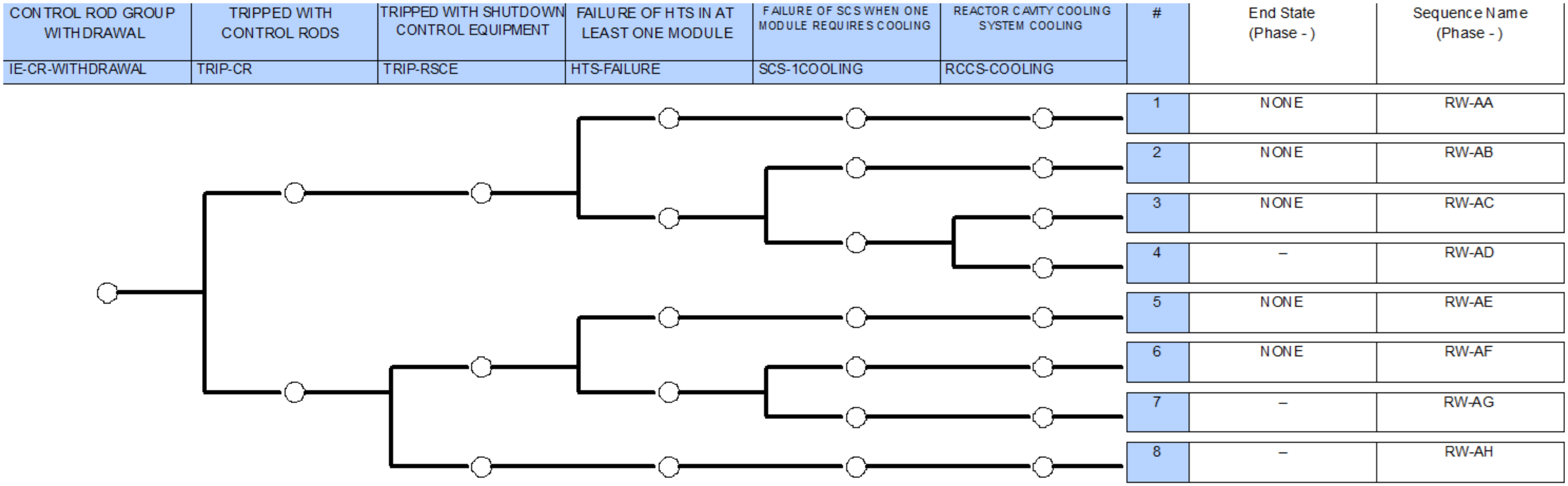

Figure A-2. Control rod group withdrawal ET.

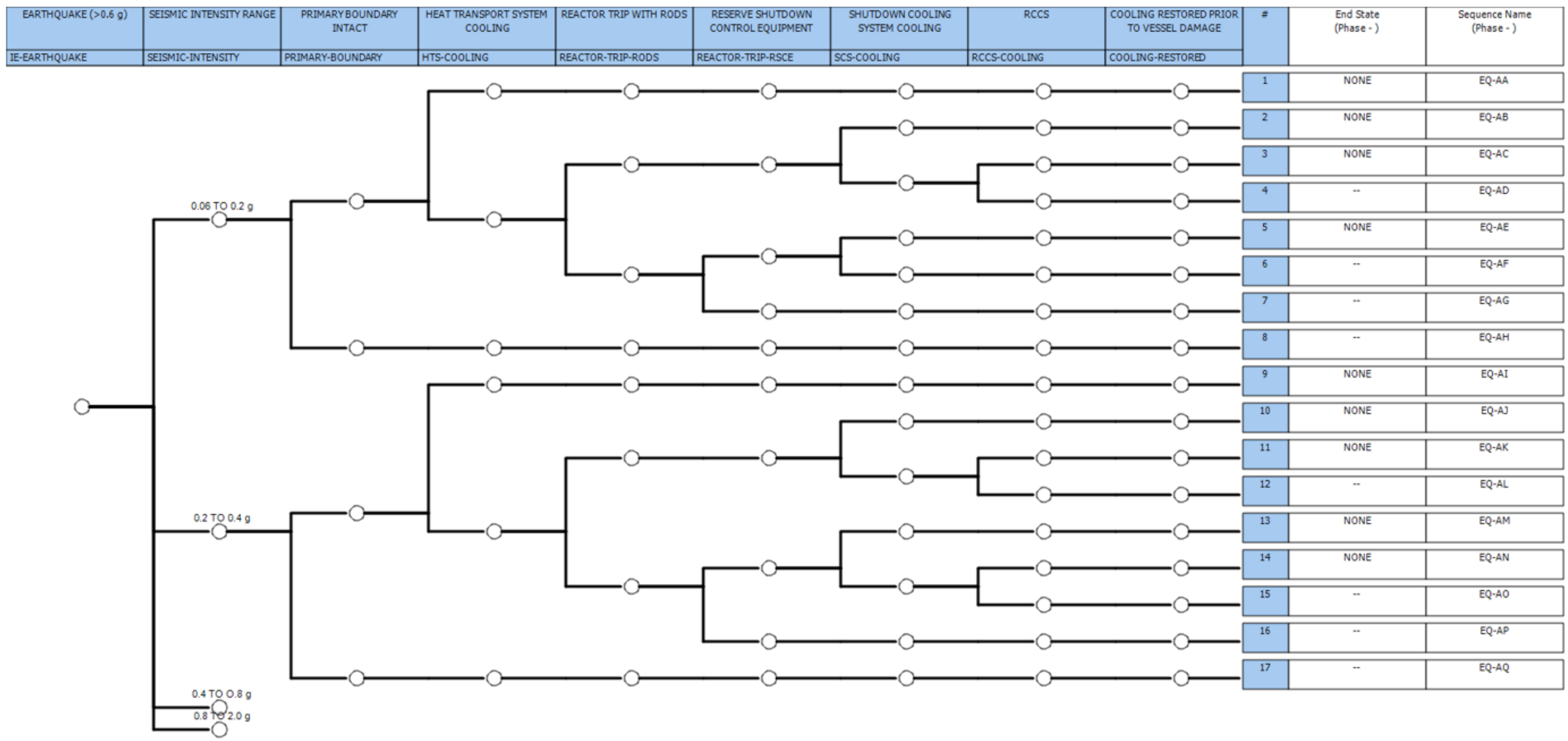

Figure A-3. Earthquake ET (1 of 2).

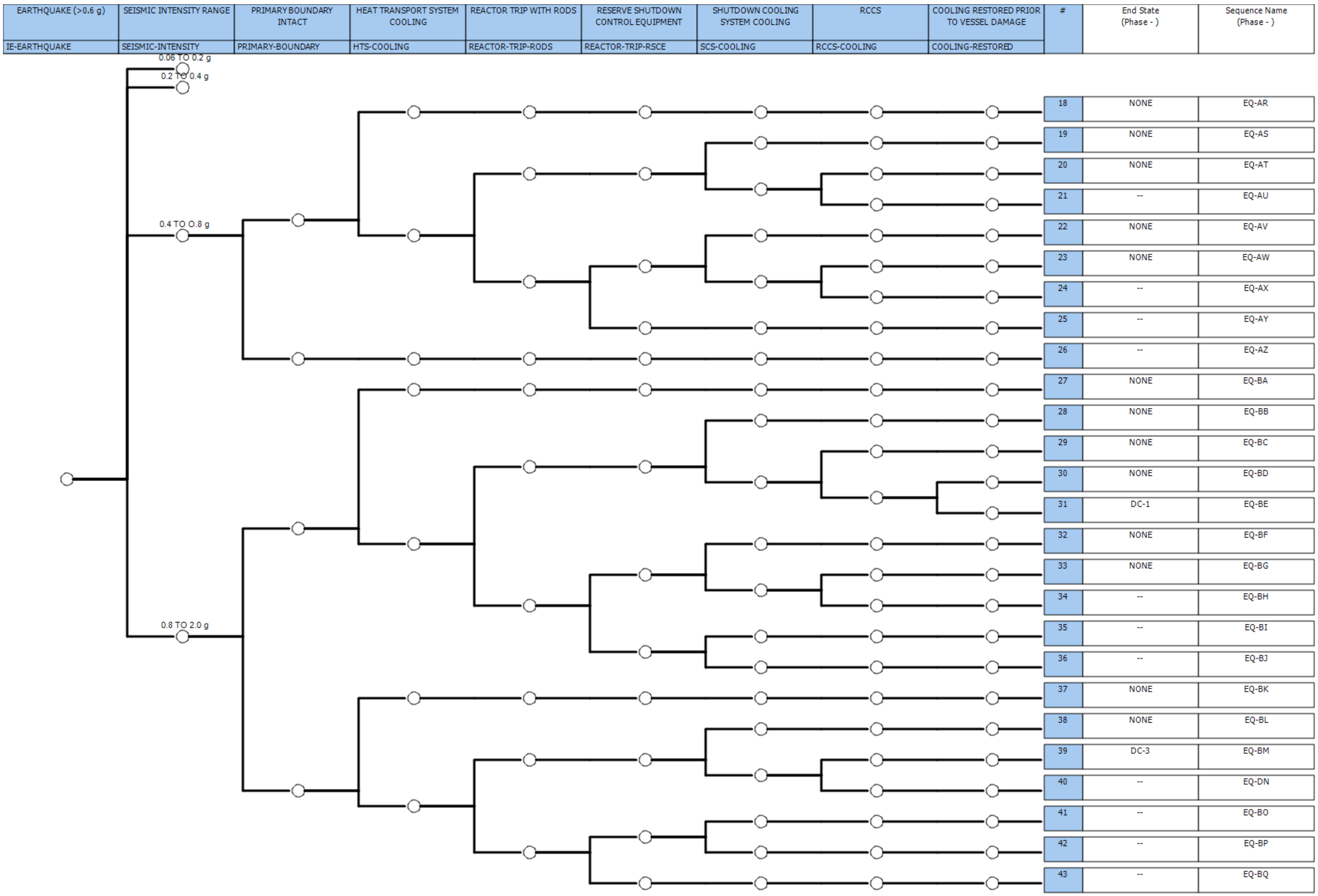

Figure A-4. Earthquake ET (2 of 2).

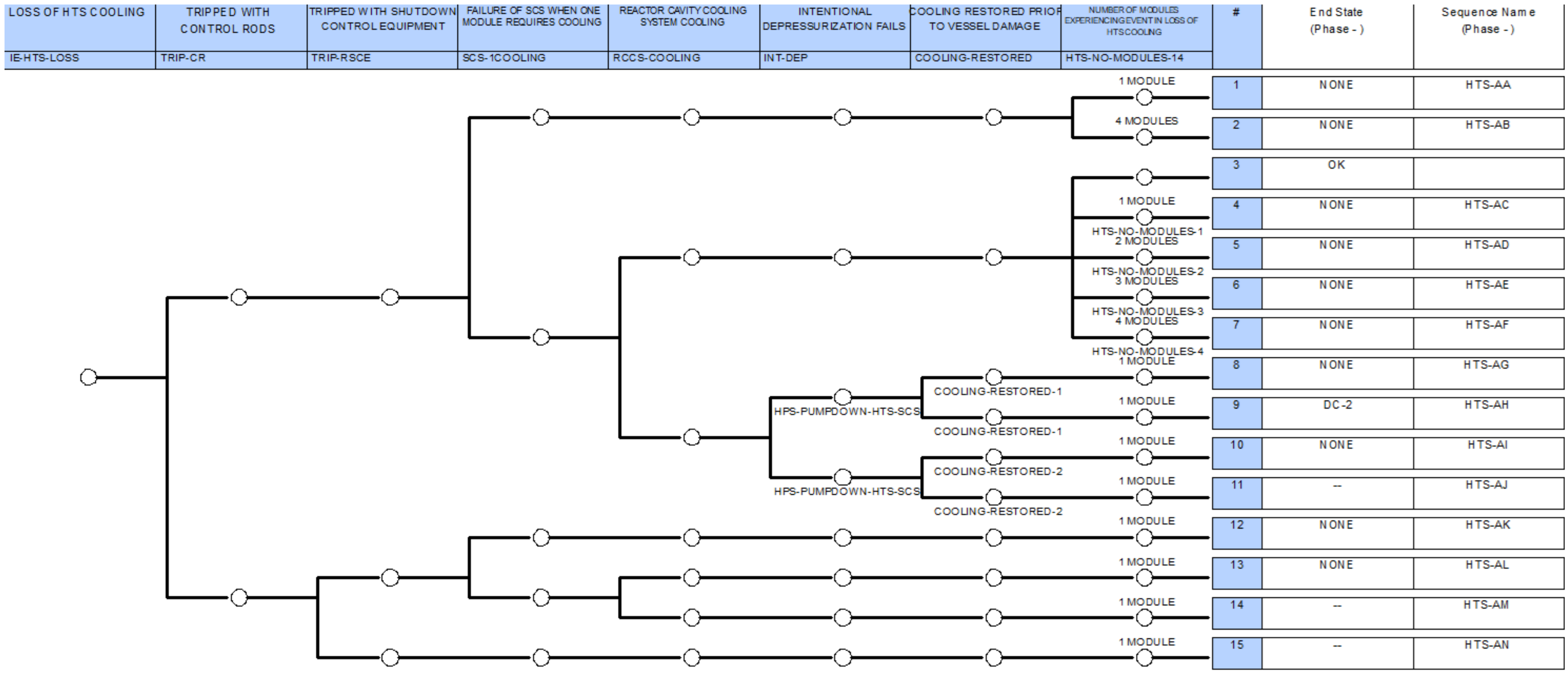

Figure A-5. Loss of heat transfer system cooling ET.

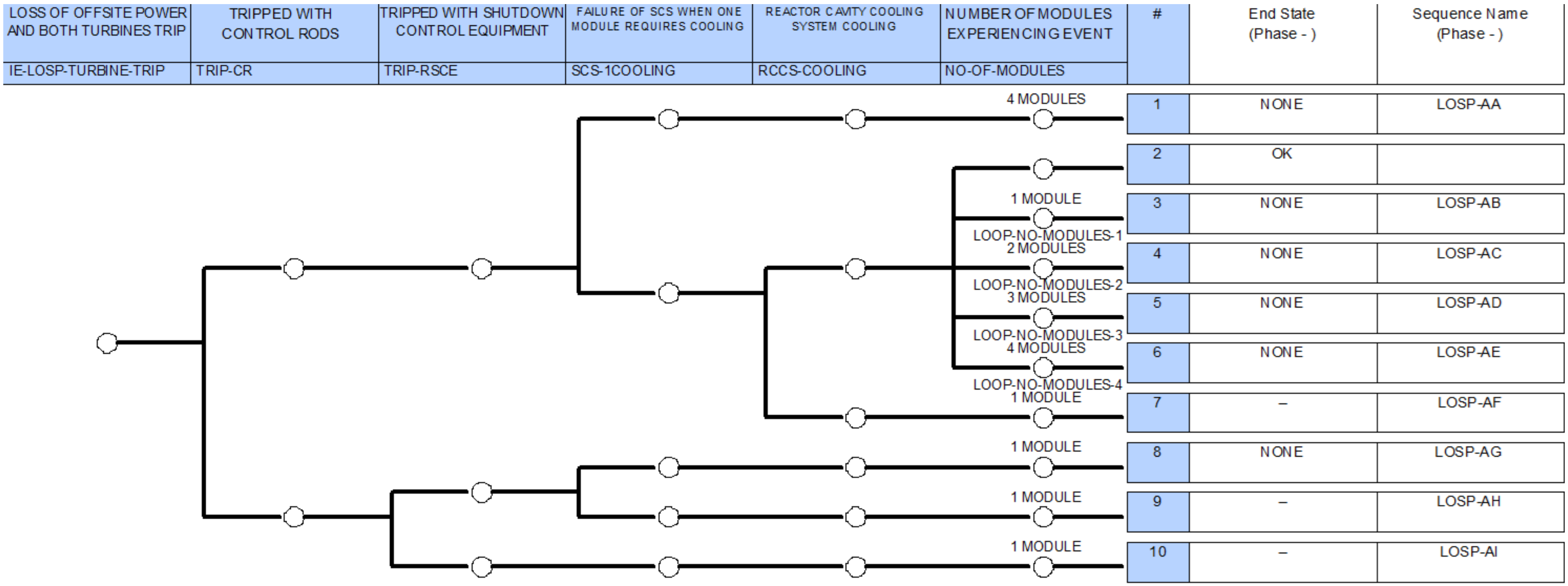

Figure A-6. LOOP and both turbines trip ET.

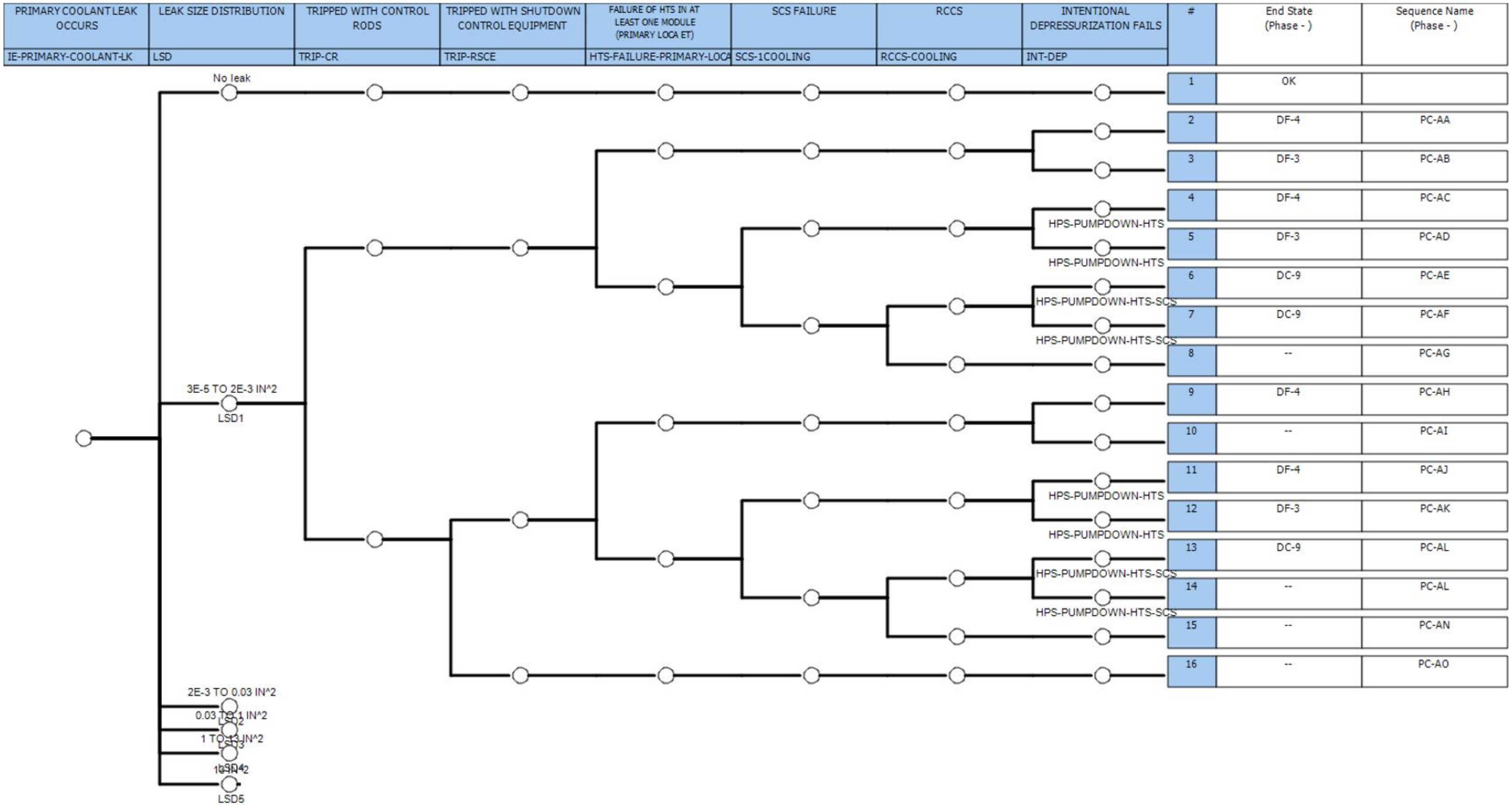

Figure A-7. Primary coolant leak ET (1 of 3).

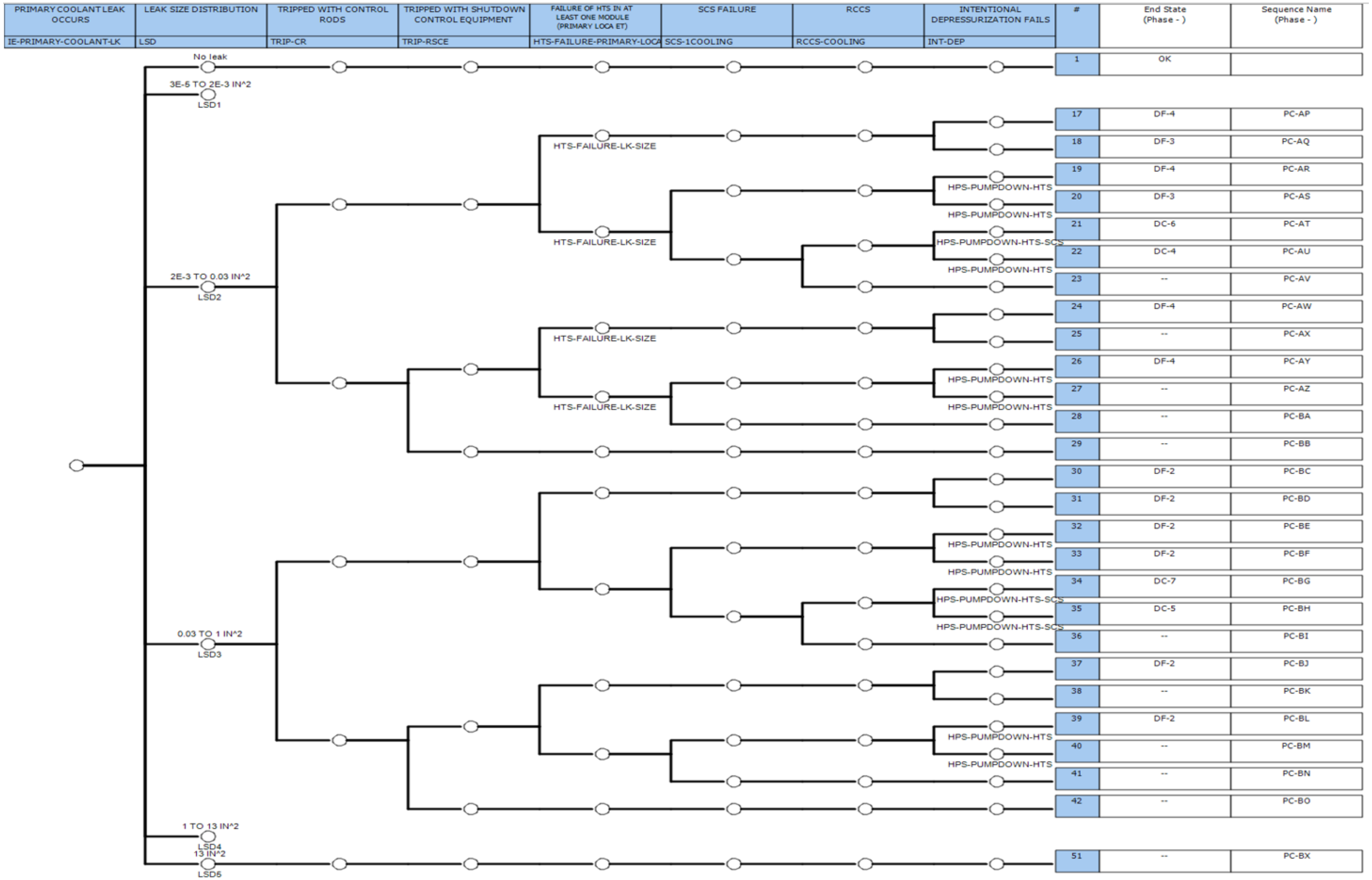

Figure A-8. Primary coolant leak ET (2 of 3).

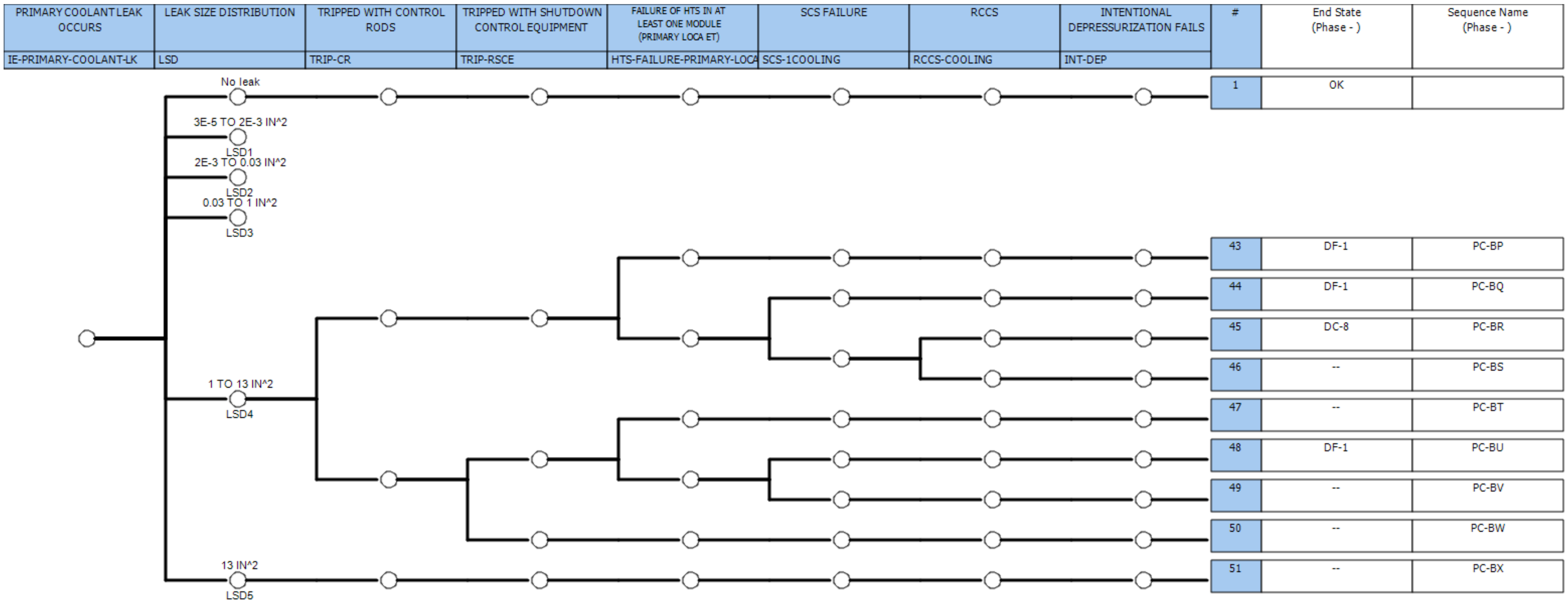

Figure A-9. Primary coolant leak ET (3 of 3).

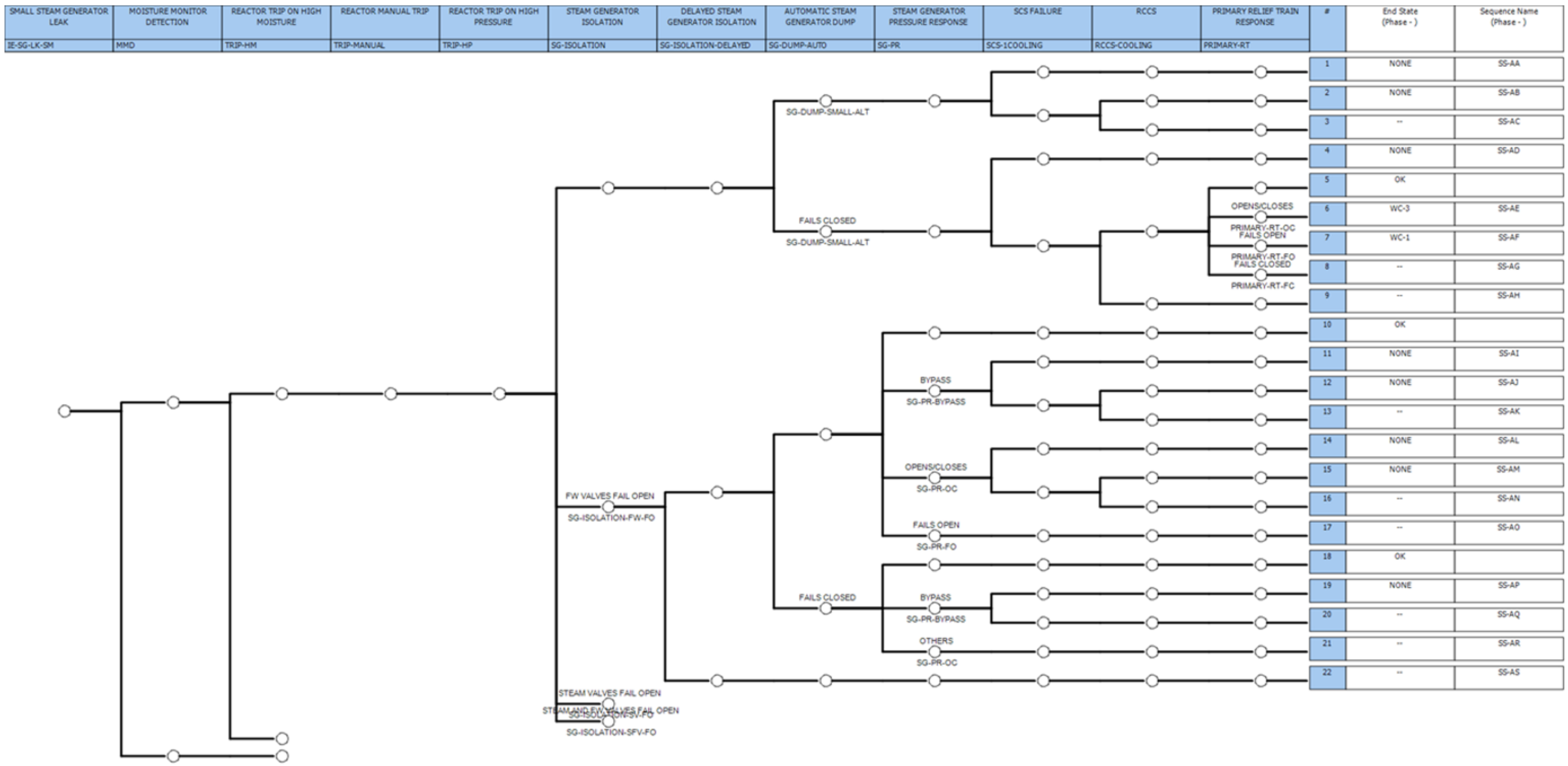

Figure A-10. Small steam generator leak (1 of 3).

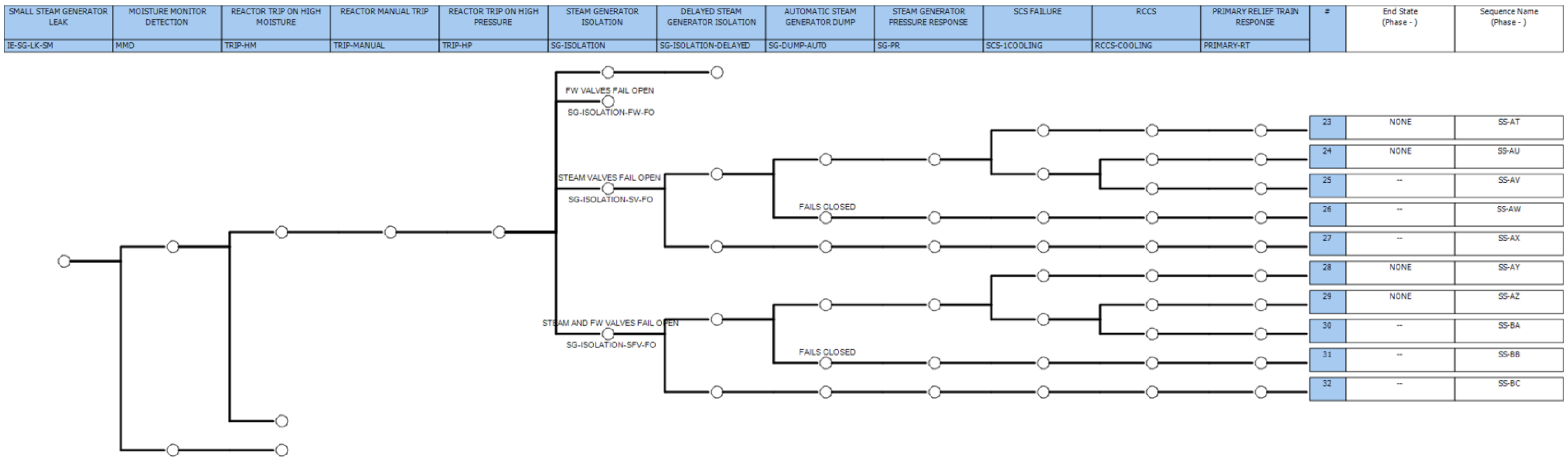

Figure A-11. Small steam generator leak (2 of 3).

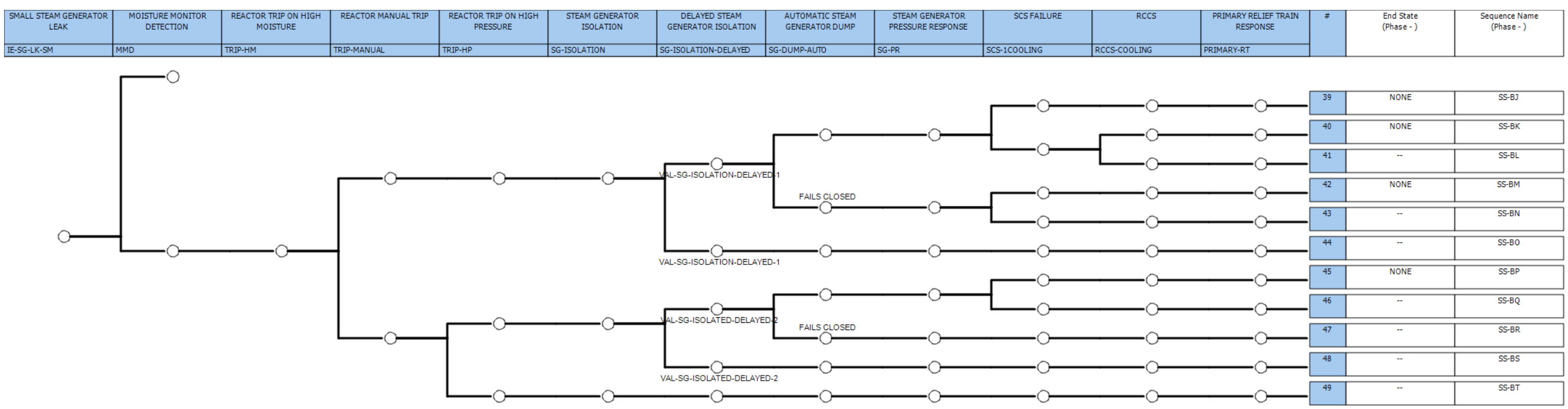

Figure A-12. Moderate steam generator leak (3 of 3).

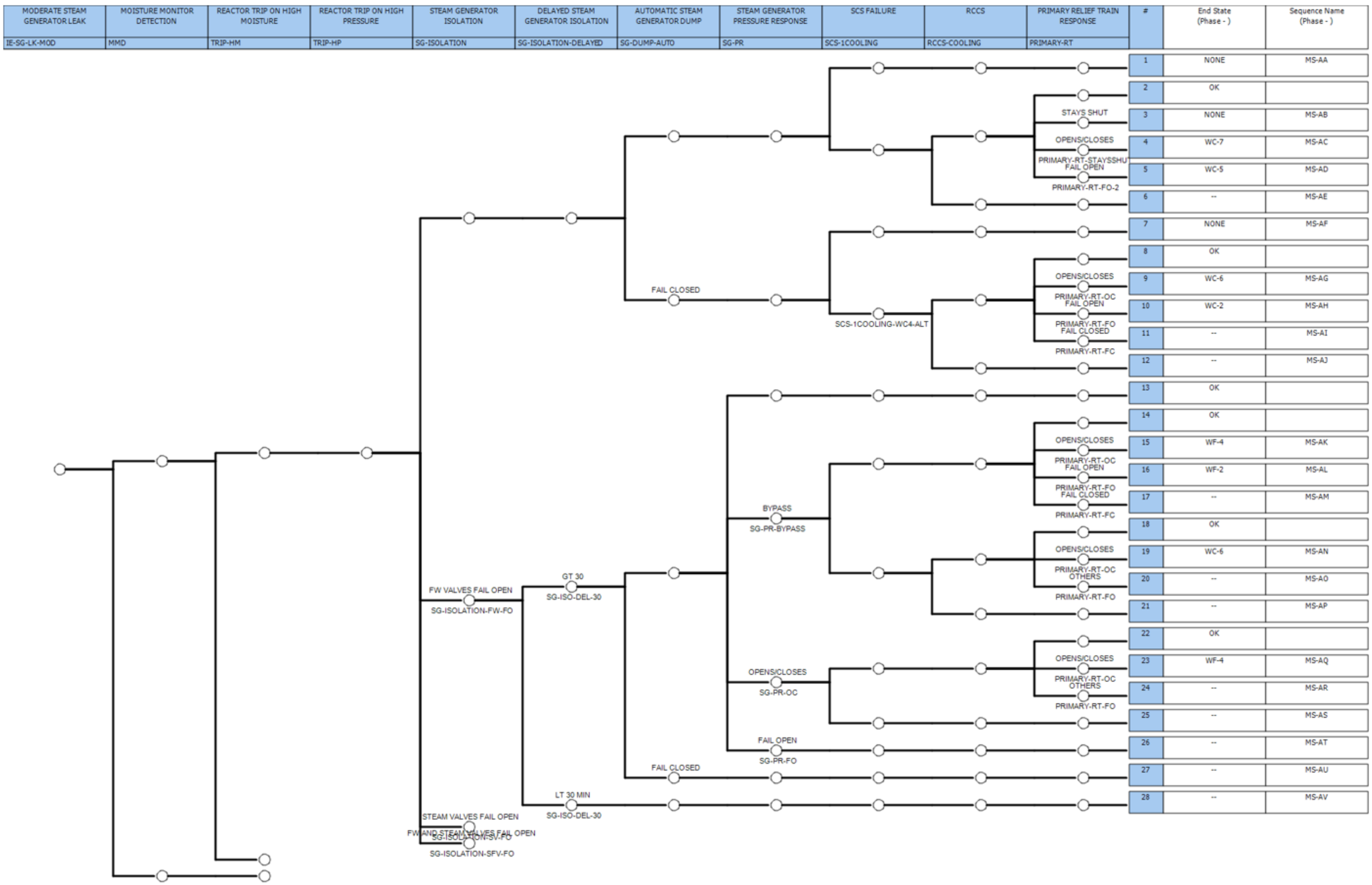

Figure A-13. Moderate steam generator leak (1 of 3).

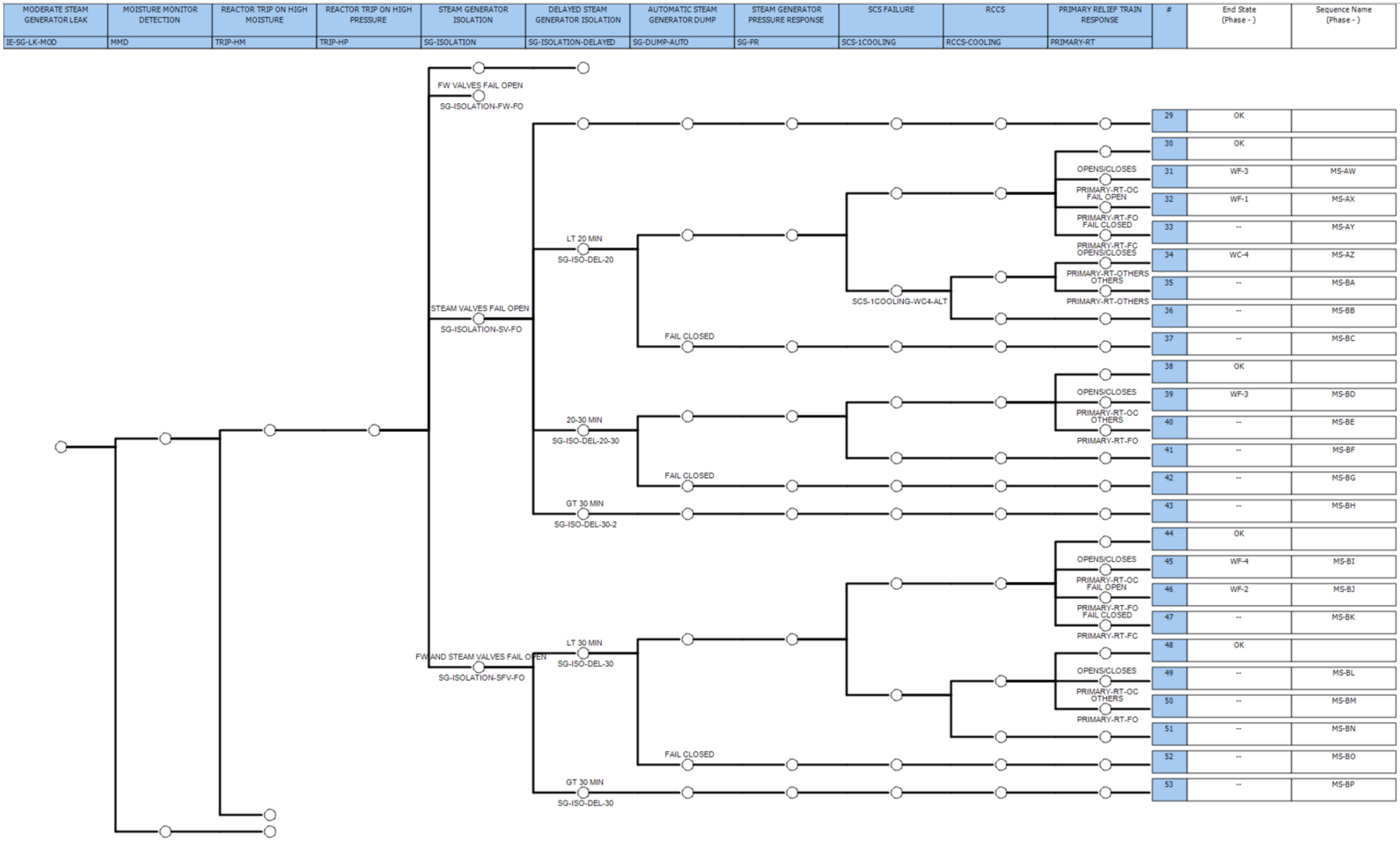

Figure A-14. Moderate steam generator leak (2 of 3).

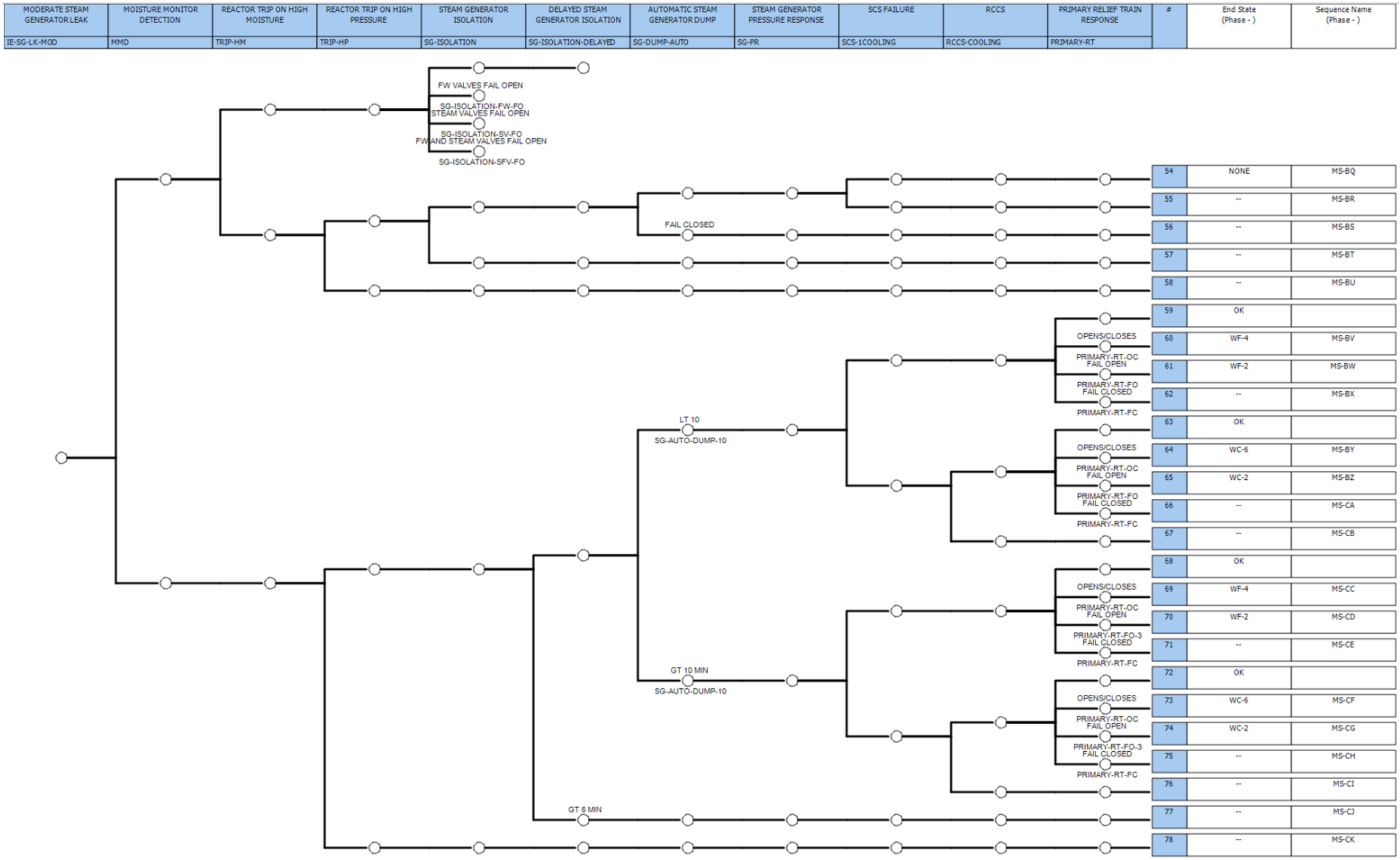

Figure A-15. Moderate steam generator leak (3 of 3).

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Appendix B FMEA Criteria

The FMEA results for BWR or PWR co-located with industrial facilities (refinery, methanol, and wood pulp and paper mill) and one specific process that is found in methanol and refinery use (syngas) are presented on the following appendices. All appendices are organized by the impacted subject of interest (e.g., nuclear power plant, syngas facility itself, public safety and perception, and economic impact). It is recognized that economic impact on either the NPP or the industrial facility will affect both the industrial facility and the NPP.

The scoring criteria used for all FMEAs followed Tables B-1 and B-2

Table B-1. Scoring criteria for FMEA ranking categories.

Score	**Severity**	**Frequency**	**Detection**
1	Little to no impact	No incidences recorded or able to avoid by siting at safe siting distance	Always quickly detected (sensor available in correct spot)
2	Small impact	1 incident recorded	Detected with aging sensor
3	Indirect impact (e.g., lower security)	1E-5 per facility year	
4	Unexpected but unhindered shutdown	1E-4 per facility year	
5	Potentially hindered shutdown and equipment damage	1E-3 per facility year	Detection available in other part of system (e.g., condensate for NPP)
6	Hindered shutdown and operations	1E-2 per facility year	
7	Damage debris, damage, personnel injuries	1E-1 per facility year	
8	Personnel fatalities and hindered shutdown	1 or more per year	
9	Severely hindered shutdown	3 or more per year	
10	Maximum impact, station blackout conditions	5 or more per year	Never detected and no sensor available

Table B-2. Risk Priority Number acronym descriptions

Acronym	**Range**	**Description**
S	1-10	Severity (1 = most severe)
F	1-10	Frequency
D	1-10	Detection (1 = easiest to detect)

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Appendix C FMEA Results for SynGas Production

The FMEA results for syngas production are listed in the following tables.

Table C-1. Nuclear power plant based FMEA results for syngas.

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for NPP	General Notes
External Power	Loss of offsite power	H_2 detonation at HTEF	S = 9 F = 1 D = 1 **Total = 9**	Severity highly dependent on NPP. Number of plants where a LOOP is a really bad day. It depends on the configuration of emergency power. The FMEA team listed severity as a range between 3 to 9. The highest number listed is used here. Must also look at next-most fragile components beyond the transmission towers and auxiliary transformers to see if they are sited at critical distances. Concentric rings of overpressure can help visualize.
		Syngas deflagration near both NPP input feed transmission towers or cables	S = 5 F = 3 D = 1 **Total = 15**	Syngas facility does not require co-location because it does not need steam from the nuclear power plant. However, syngas is a denser than air gas. If it leaks, it can be blown by the wind, probably toward nearby power transmission lines, until it meets an ignition source. Therefore, the hazard is not localized to the leakage point. On the other hand, syngas is unlikely to experience DDT resulting in a significant overpressure, although a subsonic fire may still damage power cables and equipment causing a power loss. With such considerations, the severity rank is less than hydrogen's, while the frequency rank is higher.
Primary loop transport of process steam	Loss of thermal output to HTEF Damage to turbine building equipment, possibly safety power buses, depending on the plant	Pipe Rupture after MSIV Operational vibration seismic, and erosion	S = 4 F = 2 D = 1 **Total = 8**	If safety buses are in the turbine bldg, then site the HES outside of turbine bldg. Another advantage to having the reboilers in their own building is lower temperatures in turbine building.

Table C-1 Nuclear power plant based FMEA results for SynGas Continued…

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for NPP	General Notes
Spent fuel storage (dry)	Cask tip-over due to overpressure or cask structural degradation due to heat flux	H_2 detonation at HTEF	S = 7 F = 1 D = 1 **Total = 7**	Possible damage to storage building, if used. H_2 Facility must have sufficient separation such that dry casks cannot be damaged.
		Syngas deflagration at spent fuel storage area	S = 1 F = 1 D = 1 **Total = 1**	Syngas has a relatively low heat of combustion compared to other fuels, including wood and coal. So, the heat generated from syngas fire is unlikely to cause significant damage to spent fuel casks. Therefore, the severity ranking is 1.
Electrical load to HTEF	Prompt loss of behind-the-meter electrical load to HTEF causes disruptive feedback to turbine	Unexpected immediate HTEF shutdown	S = 7 F = 1 D = 1 **Total = 7**	Would require failure of switchyard protection. The frequency is very low.
Makeup water pipeline	Loss of makeup water supply to spray ponds/cooling towers due to damaged pipeline	H_2 detonation at HTEF	S = 5 F = 1 D = 1 **Total = 5**	Possible seismic upset to pipeline to ultimate heat sink.
H_2 in NPP process	Increased levels of H_2 in steam return	H_2 piped back to NPP	S = 1 F = 1 D = 5 **Total = 5**	H_2 levels are low and are already in risk assessments of applicable NPPs.
Spray pond	Degradation of ultimate heat sink	H_2 detonation at HTEF	S = 3 F = 1 D = 1 **Total = 3**	Debris and above-water spray mechanisms, ultimate heat sink With adequate protection through distance and/or barriers this would be a severity of zero.
Cooling tower pond	Degradation of ultimate heat sink	H_2 detonation at HTEF	S = 3 F = 1 D = 1 **Total = 3**	Debris in ultimate heat sink With adequate protection through distance and/or barriers this would be a severity of zero.
Non-Safety Service water pump house	Damage and/or loss of service water building and equipment	H_2 detonation at HTEF	S = 2 F = 1 D = 1 **Total = 2**	As sited at calculated safe distance HTEF to pump house or with blast barrier.

Table C-1 Nuclear power plant based FMEA results for SynGas Continued…

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for NPP	General Notes
		Syngas fire within NPP complex	S = 4 F = 1 D = 1 **Total = 4**	While H_2 detonation hazard is controlled through a safe separation distance between nuclear power plant and possible leakage points in the HTEF, syngas may travel downwind of its leakage point until it meets an ignition source in the NPP complex. Therefore, the severity of such an event is predicted to be higher than H_2 detonation.
Forced air cooling for non-safety buildings	Damage and/or loss of NPP building HVAC equipment. Reactor building, admin building, etc.…	H_2 detonation at HTEF	S = 2 F = 1 D = 1 **Total = 2**	Can affect human operations. May have to shut down reactor.
		Syngas fire in NPP complex	S = 2 F = 1 D = 1 **Total = 2**	
NPP & H_2 administrative support	Damage to staffs' cars, office buildings and equipment	H_2 detonation at HTEF	S = 2 F = 1 D = 1 **Total = 2**	While not directly related to NPP safety, damage to support buildings can affect operations.
		Syngas fire in NPP complex	S = 2 F = 1 D = 1 **Total = 2**	
Physical protection	Damage to intrusion sensors, or triggering multiple false alarms, or empty guard posts due to evacuation	H_2 detonation at HTEF	S = 1 F = 1 D = 1 **Total = 1**	Lowered physical protection profile can lead to an opening for terrorist activity.
		Syngas dispersion reaching NPP security perimeters	S = 2 F = 1 D = 1 **Total = 2**	Syngas is toxic. Therefore, syngas dispersion in a nuclear power plant will lead to a longer evacuation of outdoor staffs compared to an instantaneous hydrogen blast explosion. Therefore, the severity ranking is 2.
NPP operation	Limited outdoor operation due to toxic concentration of syngas	Syngas dispersion reaching NPP complex	S = 3 F = 1 D = 1 **Total = 3**	Similar to the above. Syngas' toxicity can prevent outdoor operations such as maintenance actions.

Table C-1 Nuclear power plant based FMEA results for SynGas Continued…

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for NPP**	**General Notes**
Steam diversion load roughly 5% thermal	Loss of 5% load immediately	Pipe Rupture after MSIV Operational vibration seismic, and erosion	S = 0 F = 1 D = 1 **Total = 0**	NPP can handle up to 30% prompt load loss, so not a hazard.
External Supply Tanks integrity	Damage to CST, other supply tanks	H_2 detonation at HTEF	S = 0 F = 1 D = 1 **Total = 0**	As sited at calculated safe distance NPP to HTEF.
		Syngas fire in NPP complex	S = 7 F = 1 D = 1 **Total = 7**	Syngas facility does not require co-location because it does not need steam from the nuclear power plant. However, syngas is a denser than air gas. If it leaks, it can be blown by the wind toward NPP complex. Assuming there is a significant distance between the facilities, it is unlikely for the wind to blow in the right direction toward NPP, and for syngas concentration to still be above the LEL at the NPP complex. Therefore, the frequency ranking is assigned as 1.
Critical structure integrity	Damage to reactor building walls	H_2 detonation at HTEF	S = 0 F = 1 D = 1 **Total = 0**	As sited at calculated safe distance NPP to HTEF.

Table C-2. Industrial customer based FMEA results for syngas

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for Industrial Plant**	**General Notes**
Hydrogen Transport by Truck	H_2 detonation at HTEF	Fueling accident, fitting leak, valve leak, etc., along with hydrogen capture and ignition source	S = 10 F = 2 D = 1 **Total = 20**	Most severe hydrogen-based industrial accidents happen during fueling operations. Preventing accumulation opportunities through design is a key mitigator.
H_2 Storage at plant	H_2 detonation at HTEF	Tank leak/rupture with ignition source Forklift or other industrial equipment tears a hole in the tank. Possible high-wind missile strike.	S = 10 F = 2 D = 1 **Total = 20**	Severity based on volume and pressure of tank and distance. Very hard to determine frequency of a rupture event from industrial accident. Consequences are identified, but there is not a historical instance of a rupture with a detonation, only a deflagration.
H_2 production	Electrolysis stacks damaged/toppled if stacked	High winds or tornado	S = 10 F = 2 D = 1 **Total = 20**	Frequency is dependent upon location. Proper design can overcome the hazard.
H_2 Storage at plant	Tank rupture with ignition source H_2 fire at HTEF	Forklift or other industrial equipment tears a hole in the tank. Possible high-wind missile strike.	S = 10 F = 1 D = 1 **Total = 10**	Severity based on volume and pressure of tank. Potential heat flux should be a consideration in design and placement of barriers.
Multiple	H_2 detonation at HTEF	Piping or tank leak/rupture along with an ignition source	S = 10 F = 1 D = 1 **Total = 10**	Pipe rupture may cause a pipe whip and impact nearby equipment and personnel. Any flow through crack is expected to be small and may disperse in atmosphere.
Thermal delivery to hydrogen plant	Heat Exchanger Leak, steam leak, kinetic and thermal hazard	Overpressurization of HTEF supply loop - failure of relief valve	S = 5 F = 2 D = 1 **Total = 10**	Relief valve in the HTEF loop within the HTEF.
H_2 Production	Electrolysis stacks damaged/toppled if stacked	H_2 detonation at HTEF	S = 10 F = 1 D = 1 **Total = 10**	Severity based on severity and location (within stack, in system pipelines, in heat exchangers, etc.) of detonation, either way, production of H_2 would be halted. Design of facility stacking to wind/seismic codes minimizes this hazard.

Table C-2. Industrial customer based FMEA results for syngas Continued…

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for Industrial Plant	General Notes
Multiple	H_2 fire at HTEF Heat flux damage to nearby personnel, equipment, and structures	Piping or tank leak/rupture along with an ignition source	S = 8 F = 1 D = 1 **Total = 8**	National Fire Protection Agency standoff distances for hydrogen facilities must be adhered to.
Hydrogen Transport by Pipeline	Pipeline leak with ignition source H_2 detonation	Seismic event, collision accident, leaking fitting, etc.	S = 4 F = 1 D = 2 **Total = 8**	A little harder to detect unless monitors are used. Underground pipeline runs through tunnels which could trap a hydrogen cloud. Above ground structures generally protected.
			S = 5 F = 1 D = 1 **Total = 5**	May cause hydrogen jet fire if there is an ignition source and create overpressure. Depending on the leakage location, the fire and overpressure may or may not damage the RWGS reactor. The severity is higher than that of HTEF because RWGS has other incoming feedstock pipes such as CO2 that may increase the complexity of the plant and the damage of a hydrogen fire. Detection ranking is slightly lower because it should be easy to detect a change in incoming H_2 line pressure.
H_2 production	Flooding to HTEF facility, and/or damage to electrical components such as switchgear and transformers	Weather / swamp or river flooding	S = 4 F = 2 D = 1 **Total = 8**	Direct effect to operation is not known. But drying, cleaning the facility, and replacing components will cost money.
Syngas drying	Syngas leakage	Tank or pipe damage	S = 5 F = 1 D = 1 **Total = 5**	Syngas can expose plant and/or personnel to toxic and explosive hazards.
Syngas selexol separator	Syngas and selexol release	Tank or pipe damage	S = 5 F = 1 D = 1 **Total = 5**	Selexol is relatively safe since it has a low toxicity level. Prolonged skin contact may cause slight skin irritation with local redness. Syngas toxicity on the other hand is pretty high due to the carbon monoxide content. Syngas also has a fire/explosive hazard.

Table C-2. Industrial customer based FMEA results for syngas Continued…

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for Industrial Plant	General Notes
Thermal energy delivery to hydrogen plant	Nuclide contamination of the process steam	Heat Exchanger Leak	S = 7 F = 1 D = 1 **Total = 7**	By far a more significant hazard for a BWR. Cleaning and re-starting the thermal delivery system would be required. Easily detected and stopped.
H2 storage at plant	Tank leak with ignition source H2 fire at HTEF	Tank valve or fitting leak	S = 5 F = 1 D = 1 **Total = 5**	Severity based on volume and pressure of tank. National Fire Protection Agency standoff distances for hydrogen facilities must be adhered to.
Multiple	H2 product loss at HTEF Kinetic energy of leaking gas	Piping or tank leak/rupture without an ignition source	S = 2 F = 1 D = 1 **Total = 2**	Depends on pressure. Pipe rupture may cause a pipe whip and impact nearby equipment and personnel. Any flow through crack is expected to be small and may disperse in atmosphere.
N/A	Damage to nearby houses, other structures, or highway	H2 detonation at HTEF	S = 2 F = 1 D = 1 **Total = 2**	Windows, debris, and possible injuries. Design for public safety is critical by using standoff distances and/or engineered barriers as applicable.

Table C-3. Public safety and perception based FMEA results for syngas.

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Public**	**General Notes**
Hydrogen Transport by Truck	H2 detonation at HTEF	Fueling accident, fitting leak, valve leak, etc., along with ignition source	S = 8 F = 2 D = 1 **Total = 16**	Most severe hydrogen-based industrial accidents happen during fueling operations.
H2 Storage at plant	Tank rupture with ignition source H2 fire at HTEF	Forklift or other industrial equipment tears a hole in the tank. Possible high-wind missile strike.	S = 8 F = 2 D = 1 **Total = 16**	Severity based on volume and pressure of tank. Siting distance from public buildings needs to be sufficient or engineered barriers need to be in place.
Hydrogen Transport by Pipeline	Pipeline leak	Seismic event, collision accident, leaking fitting, etc.	S = 5 F = 1 D = 3 **Total = 15**	A little harder to detect unless monitors are used. Underground pipeline runs through tunnels and could trap a hydrogen cloud. Could disrupt surface roads, rail, or other underground routed services.
H2 Storage at plant	H2 detonation at HTEF	Tank rupture with ignition source Forklift or other industrial equipment tears a hole in the tank. Possible high-wind missile strike.	S = 10 F = 1 D = 1 **Total = 10**	Severity based on volume and pressure of tank.
Thermal energy delivery to hydrogen plant	Nucleide contamination of the process steam	Heat Exchanger Leak	S = 10 F = 1 D = 1 **Total = 10**	By far a more significant hazard for a BWR. Cleaning and re-starting the thermal delivery system would be required. Easily detected and stopped. There is a very low frequency of occurrence, but negative public perception would be severe.
HTEF processes/multiple	H2 detonation at HTEF	Piping or tank leak/rupture along with an ignition source	S = 10 F = 1 D = 1 **Total = 10**	Siting distance from public buildings needs to be sufficient or engineered barriers need to be in place.

Table C-3. Public safety and perception based FMEA results for syngas Continued…

Process Function	Hazard/Effects	Potential Causes/ Mechanisms of Failure	RPN for Public	General Notes
H2 production	Electrolysis stacks damaged/toppled if stacked	High winds or tornado	S = 10 F = 1 D = 1 **Total = 10**	Public perception would be moderately affected.
Multiple	Damage to nearby houses and highway	H2 detonation at HTEF	S = 10 F = 1 D = 1 **Total = 10**	Sited distance should result in minor to no damage but still would result in negative reaction from the public.
		Syngas leakage followed by downwind deflagration in public areas	S = 10 F = 1 D = 1 **Total = 10**	Severe public reaction since damage to public property and danger to public safety. Assuming RWGS and syngas pipes are located at a reasonably safe distance from public areas, the frequency of this event is low.
Multiple	H2 fire at HTEF	Piping or tank leak/rupture along with an ignition source	S = 8 F = 1 D = 1 **Total = 8**	Sited distance should result in minor to no damage but still would result in negative reaction from the public.
H2 Storage at plant	H2 detonation at HTEF	Tank valve or fitting leak with ignition source	S = 8 F = 1 D = 1 **Total = 8**	Severity based on volume and pressure of tank. Severity less than rupture due to plume instead of cloud.
H2 Storage at plant	Tank leak with ignition source H2 fire at HTEF	Tank valve or fitting leak	S = 8 F = 1 D = 1 **Total = 8**	Severity based on volume and pressure of tank.
NPP & H2 administrative support	Damage to staffs' cars, office buildings and equipment	H2 detonation at HTEF	S = 8 F = 1 D = 1 **Total = 8**	While not directly related to NPP safety, damage to support buildings can affect operations and negative public perception.
H2 Production	Electrolysis stacks damaged/toppled if stacked	H2 detonation at HTEF	S = 8 F = 1 D = 1 **Total = 8**	Decreased credibility by public.
Multiple	H2 product loss at HTEF Kinetic energy of leaking gas	Piping or tank leak/rupture without an ignition source	S = 5 F = 1 D = 1 **Total = 8**	Injuries or equipment damage could result.

Table C-3. Public safety and perception based FMEA results for syngas Continued…

Process Function	Hazard/Effects	Potential Causes/ Mechanisms of Failure	RPN for Public	General Notes
Physical protection	Damage to intrusion sensors, or triggering multiple false alarms	H2 detonation at HTEF	S = 1 F = 1 D = 1 **Total = 1**	Lowered physical protection profile can lead to an opening for terrorist activity.
Critical structure integrity	Damage to reactor building walls	H2 detonation at HTEF	S = 0 F = 1 D = 1 **Total = 8**	As sited at calculated safe distance NPP to HTEF.
Syngas production	Syngas leakage	Damage to pipes or tanks	S = 8 F = 2 D = 1 **Total = 16**	While not directly related to NPP, syngas is a hazardous gas so its accidental release to the environment near a nuclear powerplant could receive negative public backlash.

Appendix D: FMEA Results- Methanol Synthesis Facility

The FMEA results for methanol production are listed in the following tables.

Table D-1. Nuclear power plant based FMEA results for Methanol Synthesis Facility.

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for NPP**	**General Notes**
Makeup water pipeline	Loss of makeup water supply line	Methanol detonation at Methanol facility	S = 5 F = 2 D = 1 **Total** = 10	Makeup water required for proper cooling, decrease could result in insufficient cooling. Assumes makeup water pipeline is buried or covered.
Spray pond	Degradation of ultimate heat sink	Methanol detonation at Methanol facility	S = 3 F = 3 D = 1 **Total** = 9	Debris clogging pond, possibly avoidable with proper placement. Greater frequency than methanol detonation for the makeup water pipeline since spray pond is open to atmosphere.
Cooling Tower pond	Degradation of ultimate heat sink	Methanol detonation at Methanol facility	S = 3 F = 3 D = 1 **Total** = 9	Debris clogging pond, possibly avoidable with proper placement. Greater frequency than methanol detonation for the makeup water pipeline since spray pond is open to atmosphere.
Forced air cooling for non-safety buildings	Loss of HVAC equipment	Methanol detonation at Methanol facility	S = 2 F = 3 D = 1 **Total** = 6	Buildings with non-safety critical systems nor reactor building.
NPP & Methanol Facility administrative support	Damage to staffs' cars, office buildings and equipment	Methanol detonation at Methanol facility	S = 2 F = 3 D = 1 **Total** = 6	While not directly related to NPP safety, damage to support buildings can affect operations.
External Power	Loss of offsite power	Methanol detonation at Methanol facility	S = 1 F = 1 D = 1 **Total** = 1	Depends on placement. Assume sited at safe distance.

Table D-1. Nuclear power plant based FMEA results for Methanol Synthesis Facility Continued…

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for NPP**	**General Notes**
Primary loop transport of process steam	Pipe Rupture after MSIV, damage to turbine building equipment, possibly safety power buses, depending on the plant	Operational vibration seismic, and erosion	S = 1 F = 1 D = 1 **Total** = 1	Depends on placement. Assume sited at safe distance.
Non-Safety Service water pump house	Damage and/or loss of service water building and equipment	Methanol detonation at Methanol facility	S = 1 F = 1 D = 1 **Total** = 1	Depends on placement. Assume sited at safe distance.
External Supply Tanks integrity	Damage to CST, other supply tanks	Methanol detonation at Methanol facility	S = 1 F = 1 D = 1 **Total** = 1	Depends on placement. Assume sited at safe distance.
Physical protection	Damage to intrusion sensors, or triggering multiple false alarms	Methanol detonation at Methanol facility	S = 1 F = 1 D = 1 **Total** = 1	Lowered physical protection profile can lead to an opening for terrorist activity. Assume sited at safe distance.

Table D-2. Industrial customer based FMEA results for Methanol Synthesis Facility.

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for Methanol	General Notes
H2 feedstock transport by pipeline	Leakage during delivery	Fueling accident, toxicity	S = 4 F = 2 D = 2 **Total** = 16	A little harder to detect unless monitors are used. Underground pipeline runs through tunnels could trap a hydrogen cloud.
Methanol fixed bed synthesis reactor	Increased heat then pressure for reactor, detonation of methanol	Fouling in shell and reduced heat transfer	S = 8 F = 1 D = 2 **Total** = 16	Reduced heat transfer in reactor could lead to temperature increase and therefore pressure increase and possible detonation.
Multiple	Methanol detonation at Methanol Facility	Piping, reactor, or distillation column leak/rupture along with an ignition source	S = 10 F = 1 D = 1 **Total** = 10	Depends on location of break in system for concentration of methanol or other chemicals. Assume sited at safe distance.
Methanol fixed bed synthesis reactor	Methanol detonation at Methanol Facility	Runaway reaction/methanation and failed rupture disk or safety release valve	S = 10 F = 1 D = 1 **Total** = 10	Rapid increase in pressure and temperature without proper release could lead to severe detonation. Assume sited at safe distance.
Multiple	Methanol fire at Methanol Facility	Piping, reactor, or distillation column leak/rupture along with an ignition source	S = 8 F = 1 D = 1 **Total** = 8	Depends on location of break in system for concentration of methanol or other chemicals. Assume sited at safe distance.
Methanol fixed bed synthesis reactor	Methanation- Increased heat then pressure for reactor, explosion	Loss of cooling water, high CO concentration, presence of oxygen	S = 8 F = 1 D = 1 **Total** = 8	Cooling water required to keep reaction at constant temperature, increase in temperature due to less cooling could result in increased pressure and possibly detonation.
Multiple	Methanol product loss at Methanol synthesis facility, kinetic energy of leaking gas	Piping, reactor, or distillation column leak/rupture along with an ignition source	S = 2 F = 1 D = 1 **Total** = 2	Depends on pressure for magnitude of leak/rupture.

Table D-2. Industrial customer based FMEA results for Methanol Synthesis Facility Continued…

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for Methanol	General Notes
RWGS	Explosion in normal operation	Lack of fuel gas in network causing an accumulation, high pressure in fuel gas network, large variation in fuel gas density outside burner operating window, lack of combustion air, blockage of air intake, positive relative pressure in radiation zone	S = 8 F = 1 D = 1 **Total** = 8	Based on Total Energies report on Major Risk Scenarios and Safety & Environment Barriers for Steam Crackers. Severity of assets are complete destruction so high severity of hazard. Easy detection since multiple alarms and trips based on sensors and control systems to prevent the mechanisms of failure.
RWGS	Explosion in radiation section during start up	Accumulation of fuel gas due to leak or failure of ignitor	S = 8 F = 1 D = 1 **Total** = 8	Mitigation is mostly in proper execution of furnace start-up procedure.
RWGS	Radiation tube rupture which leads to fire in vicinity of furnace	furnace trip while tubes have high coke content, low hydrocarbon supply flow rate, low dilution steam flow, tube or welding defect, thermal degradation of tube, thermal shock with introduction of cold feedstock, cold naphtha entry in dilution steam	S = 5 F = 4 D = 2 **Total** = 40	Common event mostly due to trips, temperature alarm and operator action to partial trip, CO monitoring with a partial trip, and periodic inspection can mitigate. Severity is moderate due to localized nature of the break.
CO_2 capture by selexol solvent	Decreased capture efficiency of CO2, decreased MeOH synthesis, overpressure at outlet	Insufficient refrigeration of selexol solvent	S = 2 F = 2 D = 1 **Total** = 4	Assumes significant decrease in inefficiency of the selexol at capturing the CO2 and how off optimal it makes the ratio of H_2:CO.

Table D-3. Public safety and perception based FMEA results for Methanol Synthesis Facility.

Process Function	Hazard/Effects	Potential Causes/ Mechanisms of Failure	RPN for Public	General Notes
NA	Damage to nearby houses, public buildings, and highway	Methanol detonation at Methanol facility	S = 8 F = 2 D = 1 **Total** = 16	Severe public reaction since damage to public property and danger to public safety.
NPP & Methanol Facility administrative support	Damage to staffs' cars, office buildings and equipment	Methanol detonation at Methanol facility	S = 7 F = 2 D = 1 **Total** = 14	While not directly related to NPP safety, damage to support buildings and staff within would trigger severe public reaction.
H_2 feedstock transport by pipeline	Leakage during delivery	Fueling accident, toxicity	S = 7 F = 2 D = 1 **Total** = 14	Severe public reaction if externally visible/exposed structure or pipelines.
Physical protection	Damage to intrusion sensors, or triggering multiple false alarms	Methanol detonation at Methanol facility	S = 3 F = 3 D = 1 **Total** = 9	Lowered physical protection profile can lead to an opening for terrorist activity.

Table D-4. Economy based FMEA results for Methanol Synthesis Facility.

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Economic**	**General Notes**
NA	Damage to nearby houses, public buildings, and highway	Methanol detonation at Methanol facility	S = 8 F = 3 D = 1 **Total** = 24	Depends on placement. Liability- responsibility for damage repair.
NPP & Methanol Facility administrative support	Damage to staffs' cars, office buildings and equipment	Methanol detonation at Methanol facility	S = 6 F = 3 D = 1 **Total** = 18	While not directly related to NPP safety, damage to support buildings can affect operations.
Non-Safety Service water pump house	Damage and/or loss of service water building and equipment	Methanol detonation at Methanol facility	S = 5 F = 3 D = 1 **Total** = 15	Depends on placement.
Forced air cooling for non-safety buildings	Loss of HVAC equipment	Methanol detonation at Methanol facility	S = 5 F = 3 D = 1 **Total** = 15	Buildings with non-safety critical systems nor reactor building.
Makeup water pipeline	Loss of makeup water supply line	Methanol detonation at Methanol facility	S = 3 F = 3 D = 1 **Total** = 9	Makeup water required for NPP safety, cooling system, would require immediate attention and pause of normal operations.
Spray pond	Degradation of ultimate heat sink	Methanol detonation at Methanol facility	S = 3 F = 3 D = 1 **Total** = 9	Debris clogging pond, possibly avoidable with proper placement.
Cooling Tower pond	Degradation of ultimate heat sink	Methanol detonation at Methanol facility	S = 3 F = 3 D = 1 **Total** = 9	Debris clogging pond, possibly avoidable with proper placement.

Table D-4. Economy based FMEA results for Methanol Synthesis Facility Continued…

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Economic**	**General Notes**
External Power	Loss of offsite power	Methanol detonation at Methanol facility	S = 1 F = 3 D = 1 **Total** = 3	Dependent on emergency power system, how long emergency power is required. Assume safe siting distance.
Primary loop transport of process steam	Pipe Rupture after MSIV Damage to turbine building equipment, possibly safety power buses, depending on the plant	Operational vibration seismic, and erosion	S = 1 F = 3 D = 1 **Total** = 3	Primary loop is essential for heat source of power cycle. No power generation for NPP leads to no basic commodity generation. Assume safe siting distance.
Physical protection	Damage to intrusion sensors, or triggering multiple false alarms	Methanol detonation at Methanol facility	S = 1 F = 3 D = 1 **Total** = 3	Lowered physical protection profile can lead to an opening for terrorist activity. Assume safe siting distance.
External Supply Tanks integrity	Damage to CST, other supply tanks	Methanol detonation at Methanol facility	S = 1 F = 3 D = 1 **Total** = 3	Depends on placement. Assume safe siting distance.
CO2 capture by selexol solvent	Decreased capture efficiency of CO2, decreased MeOH synthesis	Insufficient refrigeration of selexol solvent	S = 2 F = 2 D = 1 **Total** = 4	Depends how inefficient the selexol becomes at capturing the CO2 and how off optimal it makes the ratio of H_2:CO.

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Appendix E: FMEA Results- Petroleum Refinery Facility

The FMEA results for a petroleum refinery facility are listed in the following tables.

Table E-1. Nuclear power plant based FMEA results for Petroleum Refinery Facility.

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for NPP	General Notes
Water contamination	toxic, settles in water, low places,	leaks of refinery products (e.g., H_2S) to the water system in NPP	S = 5 F = 3 D = 2 **Total** = 30	Potentially hindered shutdown and equipment damage for NPP. The control room environmental filtering needs to be capable of protecting the room from all potential customer hazards.
NPP & Refinery administrative support	Damage to staffs' cars, office buildings and equipment	Oil/byproducts detonation at Refinery plant	S = 6 F = 2 D = 1 **Total** = 12	NPP operations hindered until repairs are made.
Water contamination	Staff health threat	Contamination by the spill of the Refinery products or feedstocks	S = 6 F = 2 D = 1 **Total** = 12	Hindered operation of the NPP.
External Power	Loss of offsite power	Oil/byproducts detonation at Refinery facility. Flares can activate, lots of heat within the power plant	S = 5 F = 2 D = 1 **Total** = 10	Offsite power loss severity is variable, depending on the reactor design. Safe siting distance using protective barriers where necessary screen this out in a deterministic assessment.
External Supply Tanks integrity	Damage to CST, other supply tanks	Oil/byproducts detonation at Refinery plant	S = 5 F = 2 D = 1 **Total** = 10	Potentially hindered shutdown. NPP would remain offline until tank farm is repaired.
Water contamination	pH change in intake water	Contamination by the spill of the Refinery products or feedstocks	S = 5 F = 2 D = 1 **Total** = 10	Need to shut down the NPP unexpectedly due to possible damage to pumps and other equipment.

Table E-1. Nuclear power plant based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for NPP**	**General Notes**
Forced air cooling for non-safety buildings	Loss of HVAC equipment	Oil/byproducts detonation at Refinery plant	S = 4 F = 2 D = 1 **Total** = 8	NPP operations hindered until repairs are made.
Non-Safety Service water pump house	Damage and/or loss of service water building and equipment	Oil/byproducts detonation at Refinery plant	S = 4 F = 2 D = 1 **Total** = 8	NPP would need to shut down safely until repairs are made.
Water contamination	Clogging of water intake screens	Contamination by the spill of the Refinery products or feedstocks	S = 4 F = 2 D = 1 **Total** = 8	Need to shut down the NPP unexpectedly due to clogged intakes.
Physical protection	Damage to intrusion sensors, or triggering multiple false alarms	Oil/byproducts detonation at Refinery plant	S = 3 F = 2 D = 1 **Total** = 6	Lowered security posture. Impacted security but not directly affecting the nuclear safety.
Primary loop transport of process steam	Pipe Rupture after MSIV Damage to turbine building equipment, possibly safety power buses, depending on the plant	Operational vibration due to the detonation or explosion from the refinery plant	S = 3 F = 2 D = 1 **Total** = 6	More likely to affect the piping outside of the reboiler room leading to the customer. Prompt loss of heat load would occur.
Spray pond	Degradation of ultimate heat sink	Oil/byproducts detonation at Refinery plant fills the spray pond with debris	S = 3 F = 2 D = 1 **Total** = 6	NPP may have to shut down, depending on the severity of the debris.
Primary loop transport of process steam	Pipe Rupture after MSIV Damage to turbine building equipment, possibly safety power	Corrosion due to chemical release from the refinery plant	S = 1 F = 2 D = 2 **Total** = 4	Corrosives would take some time to affect the piping. Regular inspection could detect and prevent the problem.

Table E-1. Nuclear power plant based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for NPP**	**General Notes**
	buses, depending on the plant			
Makeup water pipeline	Loss of makeup water supply line	Oil/byproducts detonation at Refinery plant	S = 1 F = 2 D = 1 **Total** = 2	Would not affect NPP operation. Customer revenue would be lost until repaired.
Spent fuel storage (dry)	Damage to casks causes radiation leak	Oil/byproducts detonation at Refinery plant	S = 1 F = 2 D = 1 **Total** = 2	Dry casks are rated for fire protection.
Steam diversion load roughly 5% thermal	Prompt loss of thermal load	Oil/byproducts detonation at Refinery plant	S = 1 F = 2 D = 1 **Total** = 2	Not an issue unless the thermal diversion exceeds 30%.

Table E-2. Industrial customer based FMEA results for Petroleum Refinery Facility.

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for Methanol	General Notes
Hydrocarbon production and storage	hazardous chemical release	Leak of NAPTHA (pentane + hexane), (different compounds to catalytic reformer for gasoline)	S = 4 F = 4 D = 3 **Total** =48	Toxicity varies from 636 mg/kg to 25000 mg/kg depending on the compositions.
Desalting	Toxic BOC release	leakage of the toxic chemicals/Corrosion of the pipelines	S = 9 F = 1 D = 5 **Total** =45	Hypothetical events based on the physical understanding of the process.
Upgrading and Conversion	Fire	Ignition of a buildup of flammable vapors	S = 10 F = 4 D = 1 **Total** =40	This is based on two actual events reported in 2005. An overflowed flammable vapor cloud flowing down to the ground ignited with an idling diesel pickup truck present during the start-up of a raffinate splitter tower. 15 workers killed, 180 others injured. $21.1 billion settlement for the victims and their families. The other events happened in a distillation tower in 2006. 11 workers killed and 17 others injured. $20 million settlement for the victims and their families.
H2S storage/use at plant/Contaminant Removal	Toxic H2S release	Leakage of the H2S from storage tanks, pipes	S = 10 F = 1 D = 4 **Total** =40	Hypothetical events based on the physical understanding of the process.
Hydrocarbon production and storage	High temperature shift converter uses CO and H to create the syngas (used in methane reforming process after CO is created). Issue is carbon oxides need separated to get CO.	Leak of Carbon Monoxide	S = 4 F = 2 D = 4 **Total** =32	Carbon monoxide leakage is hard to detect, and a good amount of inhalation (3760 ppm) will cause acute toxicity.

Table E-2. Industrial customer based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for Methanol**	**General Notes**
Maintenance	Fire	Ignition of gasoline components; ignition of Naphtha. The root cause of these events come from the human error.	S = 7 F = 4 D = 1 **Total** =28	This is based on two actual events reported in CSB. One happened in 1999 during a pipe removal which transports Napthta. Several attempts fail to drain the Naptha lines. Four workers killed and one critically injured. The other happened in 2004 when ignition happened from gasoline components release during maintenance. The works fails to identify a open valve that needed to be closed. 4 workers were seriously injured. Over $13 million in property damage.
Sulfuric Acid	Corrosive, can cause leaks in pipes with worse consequences	integrity failure	S = 6 F = 2 D = 2 **Total** =24	Lamont refinery accident - destroyed (launched) tower.
Upgrading and Conversion	Explosions and fires	corrosion of vapor pipeline	S = 10 F = 2 D = 1 **Total** =20	This is a real accident that happened in Shell plant explosion in Norco, Louisiana in 1988. Seven Shell workers were killed during the explosion and 48 residents and Shell workers were injured in the explosion. The explosion released 159 million pounds (72 kt) of toxic chemicals into the air, which led to widespread damage and the evacuating of 4,500 people.
Upgrading and Conversion	Explosions and Fire; toxic hydrofluoric acid release	rupture of a steel piping component with high nickel and copper content that had corroded from HF and thinned faster than adjacent piping components with lower nickel and copper content.	S = 10 F = 2 D = 1 **Total** =20	This is based on an actual event reported in 2019 at Philadelphia Energy Solutions (PES) refinery in Philadelphia, Pennsylvania. The refinery announced it would shut down operations the same month, and filed for bankruptcy a month later. PES estimated that 5,239 pounds of HF released from piping and equipment during the incident. It estimated that 1,968 pounds of the released HF was

Table E-2. Industrial customer based FMEA results for Petroleum Refinery Facility Continued…

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for Methanol	General Notes
				contained by water spray within the unit and was processed in the refinery wastewater treatment plant, and that 3,271 pounds of HF was released to the atmosphere and was not contained by water spray. A PES also estimated that about 676,000 pounds of hydrocarbons were released during the event, of which an estimated 608,000 pounds were combusted. Marsh JLT Specialty reported that the incident resulted in an estimated property damage loss of $750 million.
Upgrading and Conversion	Fire; toxic chlorine release	temperature control failure; propane vapor release from cracked control station piping	S = 9 F = 2 D = 1 **Total** =18	This is based on an actual event reported in 2007. Four workers injured were seriously burned, including a contractor. The refinery was completely shut down for just under two months and operated at reduced capacity for nearly a year. The nearby chlorine container was affected, and 2.5 tons of chlorine has been released. Direct losses attributed to the fire were reported to exceed $50 million
Upgrading and Conversion	Explosions and Fire	Heat exchanger rupture due to high temperature hydrogen attack	S = 8 F = 2 D = 1 **Total** =16	This is based on an actual event reported in 2010. Hydrogen and naphtha at more than 500°F were released. SEVEN FATALITIES were reported. Moderate property damage from $500,000 to $2 million.
Hydrocarbon production and storage	hazardous chemical release	Leak of alkylation	S = 5 F = 1 D = 3 **Total** =15	alkylating agents are highly toxic to mucosal cells resulting in oral mucosal ulceration and effects on the intestinal mucosa.
Maintenance	Explosions and Fire	inadvertently directing air inside the regenerator through the reactor and the main column, then into the	S = 7 F = 2 D = 1 **Total** =14	This is based on an actual event reported in 2018. Shaking within a mile away. 100 metal fragments propelled (~1200 feet) within the operating areas. Exploration debris punctured

Table E-2. Industrial customer based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for Methanol**	**General Notes**
		gas concentration unit. Failure to control the air flow occurred during the shutdown. Husky Superior Refinery did not effectively implement process safety management systems		a asphalt tank, spelling out. The city evacuated 2507 residents within 2 miles north, 3miles to east and west and 10 miles south of the refinery. 36 refinery and contract workers injured (11 of them suffered from OSHA recordable injuries). This incident resulted in $550 million of on-site and $110,000 of offsite property damage.
Fractionation	Explosions and Fire	Pipe rupture	S = 6 F = 2 D = 1 **Total** =12	This is based on an actual event reported in 2012. Pipe rupture of light gas oil produced a vapor cloud that caught fire, and also enabled the release of flammable, toxic vapor. Approximately 15000 people from the surrounding area sought medical treatment due to a large plume of particulates and vapor traveling across the area
Maintenance	Fire	Operation error	S = 6 F = 2 D = 1 **Total** =12	This is based on an actual event reported in 2016. 4 workers and two others seriously injured
Fractionation	Channel Clogged	Buildup of the materials inside the channel	S = 4 F = 1 D = 3 **Total** =12	Hypothetical events based on the physical understanding of the process.
Oil storage at plant	potential chemical releases	leaks of the oil	S = 4 F = 1 D = 3 **Total** =12	Hypothetical events based on the physical understanding of the process.
CO, used as fuel and also as byproduct	Poisonous, asphyxiant	Byproduct of RWGS, also incomplete combustion	S = 3 F = 1 D = 4 **Total** =12	Hypothetical events based on the physical understanding of the process.

Table E-2. Industrial customer based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for Methanol**	**General Notes**
Benzene	Cancerous,	integrity failure	S = 4 F = 1 D = 3 **Total** =12	Hypothetical events based on the physical understanding of the process.
HF feedstock	Acidic, bone-seeker	integrity failure	S = 6 F = 1 D = 2 **Total** =12	Hypothetical events based on the physical understanding of the process.
Hydrocarbon production and storage	hazardous chemical release	Leak of propylene	S = 4 F = 1 D = 3 **Total** =12	An osmolar gap >10 mmoles/L suggests that the serum propylene glycol concentration is high enough to cause toxicity
Purging	Fire	Flammable gas leaks from a failed separation vessel where over-pressured happened and no safety mitigation system is available.	S = 5 F = 2 D =1 **Total** =10	This is a real accident that happened in Sonat Exploration Company in 1988. The fire results in the damage of the separator, piping, personal vehicles, backhoe, oil and water storage tanks, which terminates the operation of the refinery. 4 workers killed and significant damage to facility. In addition to the fatalities, the incident resulted in about $200,000 worth of damage, including the destruction of the third-stage separator, four private vehicles, and a backhoe and damage to the facility storage tanks
Upgrading and Conversion	Explosions and Fire	Operation error	S = 5 F = 2 D =1 **Total** =10	This is based on an actual event reported in 2015 at ExxonMobil Torrance Refinery. The accidents severely damaged the “electrostatic precipitator” and four contract worker were injured. A tank close to the electrostatic precipitator containing HF, water, hydrocarbons, and chemical additives was hit.

Table E-2. Industrial customer based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for Methanol**	**General Notes**
Upgrading and Conversion	Explosions and Fire	Operations error, human factors.	S = 5 F = 2 D =1 **Total** =10	This is based on an actual events reported in 2022. Naphtha filled a fuel gas mix drum that was normally only for vapors, and a flammable naphtha vapor cloud on the ground eventually ignited.
CO2 feedstock	Asphyxiant	leaks of the CO2	S = 2 F = 1 D =5 **Total** =10	Hypothetical events based on the physical understanding of the process.
Hydrocarbon production and storage	Mechanical injuries, can cut, create missiles, bend pipe, etc.	High-pressure steam leak	S = 5 F = 2 D =1 **Total** =10	The high-pressure steam may cause damage to the facilities and the surrounding staffs working in the refinery.
Hydrocarbon production and storage	hazardous chemical release	Leak of propane	S = 3 F = 1 D = 3 **Total** =9	It has been reported that brief inhalation exposures to 10,000 ppm propane cause no symptoms in humans
Hydrocarbon production and storage	hazardous chemical release	Leak of iso-butane	S = 3 F = 1 D = 3 **Total** =9	Acute oral toxicity: LD50: > 5,000 mg/kg; Acute inhalation toxicity: LC50: > 31 mg/l
Hydrocarbon production and storage	hazardous chemical release	Leak of jet fuel	S = 3 F = 1 D = 3 **Total** =9	Acute oral toxicity: LD50: > 2,000 mg/kg;
Hydrocarbon production and storage	hazardous chemical release	Leak of diesel fuel	S = 3 F = 1 D = 3 **Total** =9	Acute oral toxicity: LD50: > 5,000 mg/kg; Leak of Diesel is also a blend. Lowers the sulfur and aromatics (black soot).
Hydrocarbon production and storage	hazardous chemical release	Leak of heptane and cyclo-hexane byproduct	S = 3 F = 1 D = 3 **Total** =9	Acute oral toxicity: LD50: > 5,000 mg/kg;

Table E-2. Industrial customer based FMEA results for Petroleum Refinery Facility Continued…

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for Methanol	General Notes
Upgrading and Conversion	Explosions and Fire	Pipe rupture	S = 4 F = 2 D = 1 **Total** =8	This is based on an actual event reported in 2009. A pipe rupture causes an explosion, leading to the damage of a light structural elements. Two refinery operators and two contractors suffered serious burns
Desalting	Fire	detonation for hydrocarbons	S = 8 F = 1 D = 1 **Total** =8	Hypothetical events based on the physical understanding of the process.
Stream Quality Improvement and Blending	Fire	Buildup of the flammable vapors	S = 8 F = 1 D = 1 **Total** =8	Hypothetical events based on the physical understanding of the process.
NAPTHA storage at plant	Fires	leaks of the NAPTHA	S = 8 F = 1 D = 1 **Total** =8	Hypothetical events based on the physical understanding of the process.
Oil storage at plant	Fires	leaks of the oil	S = 8 F = 1 D = 1 **Total** =8	Hypothetical events based on the physical understanding of the process.
Upgrading and Conversion	Explosions and fires	under investigation	S = 3 F = 2 D = 1 **Total** =6	This is a real accident that happened in Shell Oil refinery in 1989. The fire burns out for three hours. Two Shell contract employees were injured. Neighborhoods were not being evacuated.
Upgrading and Conversion	Fire	valve leakage	S = 3 F = 2 D = 1 **Total** =6	This is based on an actual event reported in 2015 at Delaware City Refinery. The fire burned one hour before isolation.

Table E-2. Industrial customer based FMEA results for Petroleum Refinery Facility Continued…

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for Methanol	General Notes
Desalting	Internal flooding	Disposal water leakage	S = 2 F = 1 D = 3 **Total** =6	Hypothetical events based on the physical understanding of the process.
Feedstock (crude oil) Transport by Truck	Fueling accident, toxic chemical release	Leakage during delivery	S = 6 F = 1 D = 1 **Total** =6	Hypothetical events based on the physical understanding of the process.
Hydrocarbon production and storage	hazardous chemical release	Leak of butane	S = 2 F = 1 D = 3 **Total** =6	IDLH value: 1,600 ppm
NAPTHA storage at plant	potential chemical releases (toxicity)	leaks of the NAPTHA	S = 4 F = 1 D = 1 **Total** =4	Hypothetical events based on the physical understanding of the process.
Hydrocarbon production and storage	hazardous chemical release	Leak of sour water	S = 2 F = 1 D = 2 **Total** =4	There can be impacts of drinking water or minor damage of the facilities
Hydrocarbon production and storage	hazardous chemical release	Leak of methane	S = 1 F = 1 D = 3 **Total** =3	Methane is non-toxic
Hydrocarbon production and storage	hazardous chemical release	Leak of ethane	S = 1 F = 1 D = 3 **Total** =3	Ethane is non-toxic
Hydrocarbon production and storage	hazardous chemical release	Leak of butylene	S = 1 F = 1 D = 3 **Total** =3	limited toxicity

Table E-2. Industrial customer based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for Methanol**	**General Notes**
Hydrocarbon production and storage	hazardous chemical release	Leak of iso-butylene	S = 1 F = 1 D = 3 **Total** =3	limited toxicity
Hydrocarbon production and storage	hazardous chemical release	Leak of vacuum gasoil (BP 700F to 1000F)	S = 1 F = 1 D = 3 **Total** =3	No datasheet for gasoil. Leak of gasoline is a blend of all the different streams to make the final product.
Hydrocarbon production and storage	hazardous chemical release	Leak of asphalt (can crack it into some other streams, will auto-ignite)	S = 1 F = 1 D = 3 **Total** =3	No data available for oral acute toxicity
Hydrocarbon production and storage	hazardous chemical release	Leak of coke for burning	S = 1 F = 1 D = 3 **Total** =3	No data available for oral acute toxicity
Desalting	Failures of removing residual water	pumps malfunctions; unsuccessful splits	S = 1 F = 1 D = 3 **Total** =2	Hypothetical events based on the physical understanding of the process.

Table E-3. Public safety and perception based FMEA results for Petroleum Refinery Facility.

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Public**	**General Notes**
Hydrocarbon production and storage	hazardous chemical release	Leak of NAPTHA (pentane + hexane), (different compounds to catalytic reformer for gasoline)	S = 5 F = 4 D = 3 **Total** = 60	public concern due to the toxic chemical release
Water contamination	toxic, settles in water, low places	leaks of refinery products (e.g., H2S) to the water system in NPP	S = 8 F = 3 D = 2 **Total** = 48	Significant public concern will arise when it is announced that the water around the plant is contaminated.
Hydrocarbon production and storage	High temperature shift converter uses CO and H to create the syngas (used in methane reforming process after CO is created). Issue is carbon oxides need separated to get CO	Leak of Carbon Monoxide	S = 4 F = 2 D = 4 **Total** = 32	public concern due to the toxic chemical release (less toxicity compared to H2S)
Desalting	Toxic BOC release	leakage of the toxic chemicals/Corrosion of the pipelines	S = 5 F = 1 D = 5 **Total** = 25	public concern due to the toxic chemical release
H2S storage/use at plant/Contaminant Removal	Toxic H2S release	Leakage of the H2S from storage tanks, pipes	S = 5 F = 1 D = 4 **Total** = 20	public concern due to the toxic chemical release
H2S storage/use at plant/Contaminant Removal	Toxic H2S release	Leakage of the H2S from storage tanks, pipes	S = 5 F = 1 D = 4 **Total** = 20	public concern due to the toxic chemical release
Water contamination	Staff health threat	Contamination by the spill of the Refinery products or feedstocks	S = 8 F = 2 D = 1 **Total** = 16	Significant public concern will arise when it is announced that the water around the plant is contaminated.

Table E-3. Public safety and perception based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Public**	**General Notes**
Water contamination	pH change in intake water	Contamination by the spill of the Refinery products or feedstocks	S = 8 F = 2 D = 1 **Total** = 16	Significant public concern will arise when it is announced that the water around the plant is contaminated.
CO, used as fuel and also as byproduct	Poisonous, asphyxiant	Byproduct of RWGS, also incomplete combustion	S = 4 F = 1 D = 4 **Total** = 16	public concern due to the toxic chemical release (less toxicity compared to H2S)
N/A	Damage to nearby houses, public buildings, and highway	Oil/byproducts detonation at Refinery plant	S = 8 F = 2 D = 1 **Total** = 16	Severe public reaction since damage to public property and danger to public safety.
Oil storage at plant	potential chemical releases	leaks of the oil	S = 5 F = 1 D = 3 **Total** = 15	public concern due to the toxic chemical release
Hydrocarbon production and storage	hazardous chemical release	Leak of propylene	S = 5 F = 1 D = 3 **Total** = 15	public concern due to the toxic chemical release
CO2 feedstock	Asphyxiant	leaks of the CO2	S = 3 F = 1 D = 5 **Total** = 15	public concern due to the toxic chemical release (less toxicity compared to H2S)
Hydrocarbon production and storage	hazardous chemical release	Leak of propane	S = 5 F = 1 D = 3 **Total** = 15	public concern due to the toxic chemical release
Hydrocarbon production and storage	hazardous chemical release	Leak of iso-butane	S = 5 F = 1 D = 3 **Total** = 15	public concern due to the toxic chemical release

Table E-3. Public safety and perception based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Public**	**General Notes**
Hydrocarbon production and storage	hazardous chemical release	Leak of jet fuel	S = 5 F = 1 D = 3 **Total** = 15	public concern due to the toxic chemical release
Hydrocarbon production and storage	hazardous chemical release	Leak of diesel fuel	S = 5 F = 1 D = 3 **Total** = 15	public concern due to the toxic chemical release
Hydrocarbon production and storage	hazardous chemical release	Leak of heptane and cyclo-hexane byproduct	S = 5 F = 1 D = 3 **Total** = 15	public concern due to the toxic chemical release
NPP & Refinery administrative support	Damage to staffs' cars, office buildings and equipment	Oil/byproducts detonation at Refinery plant	S = 7 F = 2 D = 1 **Total** = 14	While not directly related to NPP safety, damage to support buildings and staff within would trigger severe public reaction.
Primary loop transport of process steam	Pipe Rupture after MSIV, Damage to turbine building equipment, possibly safety power buses, depending on the plant	Corrosion due to chemical release from the refinery plant	S = 3 F = 2 D = 2 **Total** = 12	raise public concern related to safety issue in NPP but less than the detonation.
Spent fuel storage (dry)	Damage to casks causes radiation leak	Oil/byproducts detonation at Refinery plant	S = 6 F = 2 D = 1 **Total** = 12	raise public concern regarding the large release of the radiation to the environment
Hydrocarbon production and storage	hazardous chemical release	Leak of alkylation	S = 4 F = 1 D = 3 **Total** = 12	public concern due to the toxic chemical release (less toxicity compared to H_2S)

Table E-3. Public safety and perception based FMEA results for Petroleum Refinery Facility Continued…

Process Function	Hazard/Effects	Potential Causes/ Mechanisms of Failure	RPN for Public	General Notes
Oil storage at plant	potential chemical releases	leaks of the oil	S = 4 F = 1 D = 3 **Total** = 12	public concern due to the toxic chemical release (less toxicity compared to H2S)
Benzene	Cancerous,	integrity failure	S = 4 F = 1 D = 3 **Total** = 12	public concern due to the toxic chemical release (less toxicity compared to H2S)
Hydrocarbon production and storage	hazardous chemical release	Leak of butane	S = 4 F = 1 D = 3 **Total** = 12	public concern due to the toxic chemical release (less toxicity compared to H2S)
Hydrocarbon production and storage	hazardous chemical release	Leak of methane	S = 4 F = 1 D = 3 **Total** = 12	public concern due to the toxic chemical release (less toxicity compared to H2S)
Hydrocarbon production and storage	hazardous chemical release	Leak of ethane	S = 4 F = 1 D = 3 **Total** = 12	public concern due to the toxic chemical release (less toxicity compared to H2S)
Hydrocarbon production and storage	hazardous chemical release	Leak of butylene	S = 4 F = 1 D = 3 **Total** = 12	public concern due to the toxic chemical release (less toxicity compared to H2S)
Hydrocarbon production and storage	hazardous chemical release	Leak of iso-butylene	S = 4 F = 1 D = 3 **Total** = 12	public concern due to the toxic chemical release (less toxicity compared to H2S)
Hydrocarbon production and storage	hazardous chemical release	Leak of vacuum gasoil (BP 700F to 1000F)	S = 4 F = 1 D = 3 **Total** = 12	public concern due to the toxic chemical release (less toxicity compared to H2S)

Table E-3. Public safety and perception based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Public**	**General Notes**
Hydrocarbon production and storage	hazardous chemical release	Leak of asphalt (can crack it into some other streams, will auto-ignite)	S = 4 F = 1 D = 3 **Total** = 12	public concern due to the toxic chemical release (less toxicity compared to H_2S)
Hydrocarbon production and storage	hazardous chemical release	Leak of coke for burning	S = 4 F = 1 D = 3 **Total** = 12	public concern due to the toxic chemical release (less toxicity compared to H_2S)
Primary loop transport of process steam	Pipe Rupture after MSIV. Damage to turbine building equipment, possibly safety power buses, depending on the plant	Operational vibration due to the detonation or explosion from the refinery plant	S = 5 F = 2 D = 1 **Total** = 10	raise public concern related to safety issue in NPP
Upgrading and Conversion	Explosions and Fire; toxic HF release	rupture of a steel piping component with high nickel and copper content that had corroded from HF and thinned faster than adjacent piping components with lower nickel and copper content	S = 5 F = 2 D = 1 **Total** = 10	public concern due to the toxic chemical release
Upgrading and Conversion	Fire; toxic chlorine release	temperature control failure; propane vapor release from cracked control station piping	S = 5 F = 2 D = 1 **Total** = 10	public concern due to the toxic chemical release
HF feedstock	Acidic, bone-seeker	integrity failure	S = 5 F = 2 D = 1 **Total** = 10	public concern due to the toxic chemical release
Water contamination	Clogging of water intake screens	Contamination by the spill of the Refinery products or feedstocks	S = 4 F = 2 D = 1 **Total** = 8	less concern compared to the chemistry contamination

Table E-3. Public safety and perception based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Public**	**General Notes**
Upgrading and Conversion	Fire	Ignition of a buildup of flammable vapors	S = 2 F = 4 D = 1 **Total** = 8	public concern due to the potential impacts on the air quality
Maintenance	Fire	Ignition of gasoline components; ignition of Naphtha; the root cause of these events come from the human error	S = 2 F = 4 D = 1 **Total** = 8	public concern due to the potential impacts on the air quality
Physical protection	Damage to intrusion sensors, or triggering multiple false alarms	Oil/byproducts detonation at Refinery plant	S = 3 F = 2 D = 1 **Total** = 6	Lowered physical protection profile can lead to an opening for terrorist activity.
Feedstock (crude oil) Transport by Truck	Fueling accident, toxic chemical release	Leakage during delivery	S = 6 F = 1 D = 1 **Total** = 6	raise public reaction if visible explosion can be seen on the road.
Hydrocarbon production and storage	hazardous chemical release	Leak of sour water	S = 3 F = 1 D = 2 **Total** = 6	public concern due to the toxic chemical release (less toxicity compared to H2S)
NAPTHA storage at plant	potential chemical releases (toxicity)	leaks of the NAPTHA	S = 5 F = 1 D = 1 **Total** = 5	public concern due to the toxic chemical release
Feedstock (crude oil) Transport by Truck	Fueling accident, toxic chemical release	Leakage during delivery	S = 5 F = 1 D = 1 **Total** = 5	public concern due to the toxic chemical release
NAPTHA storage at plant	potential chemical releases (toxicity)	leaks of the NAPTHA	S = 5 F = 1 D = 1 **Total** = 5	public concern due to the toxic chemical release

Table E-3. Public safety and perception based FMEA results for Petroleum Refinery Facility Continued…

Process Function	Hazard/Effects	Potential Causes/ Mechanisms of Failure	RPN for Public	General Notes
Critical structure integrity	Damage to critical structures	Oil/byproducts detonation at Refinery plant	S = 2 F = 2 D = 1 **Total** = 4	The failure of the structure integrity may raise a public concern.
External Power	Loss of offsite power	Oil/byproducts detonation at Refinery facility. Flares can activate, lots of heat within the power plant	S = 2 F = 2 D = 1 **Total** = 4	The LOOP may raise a public concern that is worse than the others.
Makeup water pipeline	Loss of makeup water supply line	Oil/byproducts detonation at Refinery plant	S = 2 F = 2 D = 1 **Total** = 4	raise limited public concern
Sulfuric Acid	Corrosive, can cause leaks in pipes with worse consequences	integrity failure	S = 1 F = 2 D = 2 **Total** = 4	limited public concern if this happen inside the refinery plant
Upgrading and Conversion	Explosions and fires	corrosion of vapor pipeline	S = 2 F = 2 D = 1 **Total** = 4	public concern due to the potential impacts on the air quality
Upgrading and Conversion	Explosions and Fire	Heat exchanger rupture due to high temperature hydrogen attack	S = 2 F = 2 D = 1 **Total** = 4	public concern due to the potential impacts on the air quality
Maintenance	Explosions and Fire	inadvertently directing air inside the regenerator through the reactor and the main column, then into the gas concentration unit. Failure to control the air flow occurred during the shutdown. Husky Superior Refinery did not effectively	S = 2 F = 2 D = 1 **Total** = 4	public concern due to the potential impacts on the air quality

Table E-3. Public safety and perception based FMEA results for Petroleum Refinery Facility Continued…

Process Function	Hazard/Effects	Potential Causes/ Mechanisms of Failure	RPN for Public	General Notes
		implement process safety management systems		
Fractionation	Explosions and Fire	Pipe rupture	S = 2 F = 2 D = 1 **Total** = 4	public concern due to the potential impacts on the air quality
Maintenance	Fire	Operation error	S = 2 F = 2 D = 1 **Total** = 4	public concern due to the potential impacts on the air quality
Purging	Fire	Flammable gas leaks from a failed separation vessel where overpressurization happened and no safety mitigation system is available	S = 2 F = 2 D = 1 **Total** = 4	public concern due to the potential impacts on the air quality
Upgrading and Conversion	Explosions and Fire	Operation error	S = 2 F = 2 D = 1 **Total** = 4	public concern due to the potential impacts on the air quality
Upgrading and Conversion	Explosions and Fire	Operations error, human factors	S = 2 F = 2 D = 1 **Total** = 4	public concern due to the potential impacts on the air quality
Upgrading and Conversion	Explosions and Fire	Pipe rupture	S = 2 F = 2 D = 1 **Total** = 4	public concern due to the potential impacts on the air quality
Upgrading and Conversion	Explosions and fires	under investigation	S = 2 F = 2 D = 1 **Total** = 4	public concern due to the potential impacts on the air quality

Table E-3. Public safety and perception based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Public**	**General Notes**
Upgrading and Conversion	Fire	valve leakage	S = 2 F = 2 D = 1 **Total** = 4	public concern due to the potential impacts on the air quality
Fractionation	Channel Clogged	Buildup of the materials inside the channel	S = 1 F = 1 D = 3 **Total** = 3	Given that the shutdown of refinery is safe enough. No specific concern will arise
Fractionation	Channel Clogged	Buildup of the materials inside the channel	S = 1 F = 1 D = 3 **Total** = 3	Given that the shutdown of refinery is safe enough. No specific concern will arise
Desalting	Internal flooding	Disposal water leakage	S = 1 F = 1 D = 3 **Total** = 3	Assume the flooding only impacts internally. No public concern raises
Control of plant.	Loss of cooling water	Flares can activate, lots of heat within the power plant	S = 1 F = 2 D = 1 **Total** = 2	Given that the shutdown of NPP is safe enough. No specific concern will arise
Cooling Tower pond	Degradation of ultimate heat sink	Oil/byproducts detonation at Refinery plant fills the cooling tower pond with debris	S = 1 F = 2 D = 1 **Total** = 2	Given that the shutdown of NPP is safe enough. No specific concern will arise
External Supply Tanks integrity	Damage to CST, other supply tanks	Oil/byproducts detonation at Refinery plant	S = 1 F = 2 D = 1 **Total** = 2	Given that the shutdown of NPP is safe enough. No specific concern will arise
Forced air cooling for non-safety buildings	Loss of HVAC equipment	Oil/byproducts detonation at Refinery plant	S = 1 F = 2 D = 1 **Total** = 2	Given that the shutdown of NPP is safe enough. No specific concern will arise

Table E-3. Public safety and perception based FMEA results for Petroleum Refinery Facility Continued…

Process Function	Hazard/Effects	Potential Causes/ Mechanisms of Failure	RPN for Public	General Notes
Non-Safety Service water pump house	Damage and/or loss of service water building and equipment	Oil/byproducts detonation at Refinery plant	S = 1 F = 2 D = 1 **Total** = 2	Given that the shutdown of NPP is safe enough. No specific concern will arise
Spray pond	Degradation of ultimate heat sink	Oil/byproducts detonation at Refinery plant fills the spray pond with debris	S = 1 F = 2 D = 1 **Total** = 2	Given that the shutdown of NPP is safe enough. No specific concern will arise
Steam diversion load roughly 5% thermal	Prompt loss of thermal load	Oil/byproducts detonation at Refinery plant	S = 1 F = 2 D = 1 **Total** = 2	Given that the shutdown of NPP is safe enough. No specific concern will arise
Stream Quality Improvement and Blending	Fire	Buildup of the flammable vapors	S = 2 F = 1 D = 1 **Total** = 2	public concern due to the potential impacts on the air quality
NAPTHA storage at plant	Fires	leaks of the NAPTHA	S = 2 F = 1 D = 1 **Total** = 2	public concern due to the potential impacts on the air quality
Oil storage at plant	Fires	leaks of the oil	S = 2 F = 1 D = 1 **Total** = 2	public concern due to the potential impacts on the air quality
Hydrocarbon production and storage	Mechanical injuries, can cut, create missiles, bend pipe, etc.	High-pressure steam leak	S = 1 F = 2 D = 1 **Total** = 2	The concern only valid inside refinery. No public concern
Desalting	Fire	detonation for hydrocarbons	S = 2 F = 1 D = 1 **Total** = 2	public concern due to the potential impacts on the air quality

Table E-3. Public safety and perception based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Public**	**General Notes**
Stream Quality Improvement and Blending	Fire	Buildup of the flammable vapors	S = 2 F = 1 D = 1 **Total** = 2	public concern due to the potential impacts on the air quality
NAPTHA storage at plant	Fires	leaks of the NAPTHA	S = 2 F = 1 D = 1 **Total** = 2	public concern due to the potential impacts on the air quality
Oil storage at plant	Fires	leaks of the oil	S = 2 F = 1 D = 1 **Total** = 2	public concern due to the potential impacts on the air quality
Desalting	Failures of removing residual water	pumps malfunctions; unsuccessful splits	S = 1 F = 1 D = 2 **Total** = 2	Assume the flooding only impacts internally. No public concern raises

Table E-4. Economy based FMEA results for Petroleum Refinery Facility

Process Function	Hazard/Effects	Potential Causes/ Mechanisms of Failure	RPN for Economic	General Notes
Upgrading and Conversion	Fire	Ignition of a buildup of flammable vapors	S = 10 F = 4 D = 1 **Total** = 40	This is based on two actual events reported in 2005. $21.1 billion settlement for the victims and their families. The other events happened in a distillation tower in 2006. $20 million settlement for the victims and their families.
Maintenance	Fire	Ignition of gasoline components; ignition of Naphtha. The root cause of these events come from the human error.	S = 8 F = 4 D = 1 **Total** = 32	This is based on two actual events reported in CSB. One happened in 1999 during a pipe removal which transports Napthta. Over $13 million in property damage.
Hydrocarbon production and storage	hazardous chemical release	Leak of NAPTHA (pentane + hexane), (different compounds to catalytic reformer for gasoline)	S = 2 F = 4 D = 3 **Total** = 24	no additional evidence is provided for the revenue loss
Water contamination	toxic, settles in water, low places,	leaks of refinery products (e.g., H2S) to the water system in NPP	S = 4 F = 3 D = 2 **Total** = 24	Loss of revenue expected for potentially hindered shutdown and equipment damage for NPP. The control room environmental filtering needs to be capable of protecting the room from all potential customer hazards.
Maintenance	Explosions and Fire	inadvertently directing air inside the regenerator through the reactor and the main column, then into the gas concentration unit. Failure to control the air flow occurred during the shutdown. Husky Superior Refinery did not effectively implement process safety management systems	S = 10 F = 2 D = 1 **Total** = 20	This is based on an actual events reported in 2018. This incident resulted in $550 million of on-site and $110,000 of offsite property damage.
Upgrading and Conversion	Explosions and Fire; toxic HF release	rupture of a steel piping component with high nickel and copper content that had corroded from HF and thinned faster than adjacent piping components with lower nickel and copper content.	S = 10 F = 2 D = 1 **Total** = 20	This is based on an actual event reported in 2019 at PES refinery in Philadelphia, Pennsylvania. Marsh JLT Specialty reported that the incident resulted in an estimated property damage loss of $750 million.

Table E-4. Economy based FMEA results for Petroleum Refinery Facility Continued…

Process Function	Hazard/Effects	Potential Causes/ Mechanisms of Failure	RPN for Economic	General Notes
Upgrading and Conversion	Fire; toxic chlorine release	temperature control failure; propane vapor release from cracked control station piping	S = 9 F = 2 D = 1 **Total** = 18	This is based on an actual events reported in 2007.The nearby chlorine container was affected and 2.5 tons of chlorine has been released. Direct losses attributed to the fire were reported to exceed $50 million
Purging	Fire	Flammable gas leaks from a failed separation vessel where overpressurization happened and no safety mitigation system is available.	S = 8 F = 2 D = 1 **Total** = 16	This is a real accident happened in Sonat Exploration Company in 1988. the incident resulted in about $200,000 worth of damage, including the destruction of the third-stage separator, four private vehicles, and a backhoe and damage to the facility storage tanks
Upgrading and Conversion	Explosions and Fire	Heat exchanger rupture due to high temperature hydrogen attack	S = 8 F = 2 D = 1 **Total** = 16	This is based on an actual events reported in 2010. Moderate property damage from $500,000 to $2 million.
External Power to NPP	shutdown loss of revenue	weather	S = 2 F = 7 D = 1 **Total** = 14	no additional evidence is provided for the revenue loss
External Power to Refinery	shutdown loss of revenue	weather	S = 2 F = 7 D = 1 **Total** = 14	no additional evidence is provided for the revenue loss
Upgrading and Conversion	Explosions and fires	corrosion of vapor pipeline	S = 7 F = 2 D = 1 **Total** = 14	This is a real accident happened in Shell plant explosion in Norco, Louisiana in 1988. The explosion released 159 million pounds (72 kt) of toxic chemicals into the air, which led to widespread damage and the evacuating of 4,500 people.
Fractionation	Explosions and Fire	Pipe rupture	S = 6 F = 2 D = 1 **Total** = 12	Approximately 15000 people from the surrounding area sought medical treatment due to a large plume of particulates and vapor traveling across the area

Table E-4. Economy based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Economic**	**General Notes**
Sulfuric Acid	Corrosive, can cause leaks in pipes with worse consequences	integrity failure	S = 3 F = 2 D = 2 **Total** = 12	Lamont refinery accident - destroyed (launched) tower. This may need to the shutdown of the refinery plant. But no specific amount of the dollar value loss specified.
Desalting	Toxic BOC release	leakage of the toxic chemicals/Corrosion of the pipelines	S = 2 F = 1 D = 5 **Total** = 10	no additional evidence is provided for the revenue loss
External Supply Tanks integrity	Damage to CST, other supply tanks	Oil/byproducts detonation at Refinery plant	S = 5 F = 2 D = 1 **Total** = 10	Potentially hindered shutdown. NPP would remain offline until tank farm is repaired.
Benzene	Cancerous,	integrity failure	S = 3 F = 1 D = 3 **Total** = 9	potential shut down of refinery, leading to revenue loss.
H2S storage/use at plant/Contaminant Removal	Toxic H2S release	Leakage of the H2S from storage tanks, pipes	S = 2 F = 1 D = 4 **Total** = 8	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	High temperature shift converter uses CO and H to create the syngas (used in methane reforming process after CO is created). Issue is carbon oxides need separated to get CO.	Leak of Carbon Monoxide	S = 1 F = 2 D = 4 **Total** = 8	no additional evidence is provided for the revenue loss
Control of plant	Loss of cooling water	Flares can activate, lots of heat within the power plant	S = 4 F = 2 D = 1 **Total** = 8	Loss of revenue expected during the shutdown of the NPP.

Table E-4. Economy based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Economic**	**General Notes**
External Supply Tanks integrity	Damage to CST, other supply tanks	Oil/byproducts detonation at Refinery plant	S = 4 F = 2 D = 1 **Total** = 8	Loss of revenue expected for potentially hindered shutdown. NPP would remain offline until tank farm is repaired.
Forced air cooling for non-safety buildings	Loss of HVAC equipment	Oil/byproducts detonation at Refinery plant	S = 4 F = 2 D = 1 **Total** = 8	Loss of revenue expected when NPP operations hindered until repairs are made.
Non-Safety Service water pump house	Damage and/or loss of service water building and equipment	Oil/byproducts detonation at Refinery plant	S = 4 F = 2 D = 1 **Total** = 8	NPP would need to shut down safely until repairs are made, leading to loss of revenue.
NPP & Refinery administrative support	Damage to staffs' cars, office buildings and equipment	Oil/byproducts detonation at Refinery plant	S = 4 F = 2 D = 1 **Total** = 8	NPP operations hindered until repairs are made, leading to loss of revenue.
Water contamination	Staff health threat	Contamination by the spill of the Refinery products or feedstocks	S = 4 F = 2 D = 1 **Total** = 8	Hindered operation of the NPP, leading to loss of revenue.
Water contamination	pH change in intake water	Contamination by the spill of the Refinery products or feedstocks	S = 4 F = 2 D = 1 **Total** = 8	Need to shut down the NPP unexpectedly due to possible damage to pumps and other equipment, leading to loss of revenue.
Water contamination	Clogging of water intake screens	Contamination by the spill of the Refinery products or feedstocks	S = 4 F = 2 D = 1 **Total** = 8	Need to shut down the NPP unexpectedly due to clogged intakes,, leading to loss of revenue.
Desalting	Internal flooding	Disposal water leakage	S = 2 F = 1 D = 3 **Total** = 6	no additional evidence is provided for the revenue loss

Table E-4. Economy based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Economic**	**General Notes**
Fractionation	Channel Clogged	Buildup of the materials inside the channel	S = 3 F = 1 D = 2 **Total** = 6	no additional evidence is provided for the revenue loss
HF feedstock	Acidic, bone-seeker	integrity failure	S = 3 F = 2 D = 1 **Total** = 6	potential shut down of refinery, leading to revenue loss.
Hydrocarbon production and storage	Mechanical injuries, can cut, create missiles, bend pipe, etc.	High-pressure steam leak	S = 2 F = 1 D = 3 **Total** = 6	potential shut down of refinery, leading to revenue loss.
Hydrocarbon production and storage	hazardous chemical release	Leak of jet fuel	S = 2 F = 1 D = 3 **Total** = 6	no additional evidence is provided for the revenue loss
Oil storage at plant	potential chemical releases	leaks of the oil	S = 2 F = 1 D = 3 **Total** = 6	no additional evidence is provided for the revenue loss
Upgrading and Conversion	Explosions and fires	under investigation	S = 3 F = 2 D = 1 **Total** = 6	This is a real accident happened in Shell Oil refinery in 1989. The fire burn out for three hours and may lead to the shutdown of the refinery plant. Two Shell contract employees were injured. Neighborhoods were not being evacuated.
Cooling Tower pond	Degradation of ultimate heat sink	Oil/byproducts detonation at Refinery plant fills the cooling tower pond with debris	S = 3 F = 2 D = 1 **Total** = 6	NPP may have to shut down, depending on the severity of the debris, leading to loss of revenue.
Spray pond	Degradation of ultimate heat sink	Oil/byproducts detonation at Refinery plant fills the spray pond with debris	S = 3 F = 2 D = 1 **Total** = 6	NPP may have to shut down, depending on the severity of the debris and result in revenue loss.

Table E-4. Economy based FMEA results for Petroleum Refinery Facility Continued…

Process Function	Hazard/Effects	Potential Causes/ Mechanisms of Failure	RPN for Economic	General Notes
CO_2 feedstock	Asphyxiant	leaks of the CO_2	S = 1 F = 1 D = 5 **Total** = 5	no additional evidence is provided for the revenue loss
CO, used as fuel and also as byproduct	Poisonous, asphyxiant	Byproduct of RWGS, also incomplete combustion	S = 1 F = 1 D = 4 **Total** = 4	no additional evidence is provided for the revenue loss
External Power to NPP	shutdown loss of revenue	fire/detonation	S = 2 F = 2 D = 1 **Total** = 4	no additional evidence is provided for the revenue loss
Maintenance	Fire	Operation error	S = 2 F = 2 D = 1 **Total** = 4	no additional evidence is provided for the revenue loss
Upgrading and Conversion	Explosions and Fire	Pipe rupture	S = 2 F = 2 D = 1 **Total** = 4	no additional evidence is provided for the revenue loss
Upgrading and Conversion	Explosions and Fire	Operation error	S = 2 F = 2 D = 1 **Total** = 4	no additional evidence is provided for the revenue loss
Upgrading and Conversion	Fire	valve leakage	S = 2 F = 2 D = 1 **Total** = 4	no additional evidence is provided for the revenue loss
Upgrading and Conversion	Explosions and Fire	Operations error, human factors.	S = 2 F = 2 D = 1 **Total** = 4	no additional evidence is provided for the revenue loss

Table E-4. Economy based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Economic**	**General Notes**
Physical protection	Damage to intrusion sensors, or triggering multiple false alarms	Oil/byproducts detonation at Refinery plant	S = 2 F = 2 D = 1 **Total** = 4	Lowered security posture. Impacted security but not directly affecting the nuclear safety
Primary loop transport of process steam	Pipe Rupture after MSIV, Damage to turbine building equipment, possibly safety power buses, depending on the plant	Corrosion due to chemical release from the refinery plant	S = 1 F = 2 D = 2 **Total** = 4	Corrosives would take some time to affect the piping. Regular inspection could detect and prevent the problem.
Hydrocarbon production and storage	hazardous chemical release	Leak of vacuum gasoil (BP 700F to 1000F)	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of asphalt (can crack it into some other streams, will auto-ignite)	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of coke for burning	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of methane	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of butylene	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of iso-butylene	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss

Table E-4. Economy based FMEA results for Petroleum Refinery Facility Continued…

Process Function	Hazard/Effects	Potential Causes/ Mechanisms of Failure	RPN for Economic	General Notes
Hydrocarbon production and storage	hazardous chemical release	Leak of propane	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of butane	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of ethane	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of propylene	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of alkylation	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of diesel fuel	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of iso-butane	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of heptane and cyclo-hexane byproduct	S = 1 F = 1 D = 3 **Total** = 3	no additional evidence is provided for the revenue loss

Table E-4. Economy based FMEA results for Petroleum Refinery Facility Continued…

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Economic**	**General Notes**
Desalting	Fire	detonation for hydrocarbons	S = 2 F = 1 D = 1 **Total** = 2	no additional evidence is provided for the revenue loss
Desalting	Failures of removing residual water	pumps malfunctions; unsuccessful splits	S = 1 F = 1 D = 2 **Total** = 2	no additional evidence is provided for the revenue loss. Lower bound is specified.
Feedstock (crude oil) Transport by Truck	Fueling accident, toxic chemical release	Leakage during delivery	S = 2 F = 1 D = 1 **Total** = 2	no additional evidence is provided for the revenue loss
Hydrocarbon production and storage	hazardous chemical release	Leak of sour water	S = 1 F = 1 D = 2 **Total** = 2	no additional evidence is provided for the revenue loss
NAPTHA storage at plant	Fires	leaks of the NAPTHA	S = 2 F = 1 D = 1 **Total** = 2	no additional evidence is provided for the revenue loss
NAPTHA storage at plant	potential chemical releases (toxicity)	leaks of the NAPTHA	S = 2 F = 1 D = 1 **Total** = 2	no additional evidence is provided for the revenue loss
Oil storage at plant	Fires	leaks of the oil	S = 2 F = 1 D = 1 **Total** = 2	no additional evidence is provided for the revenue loss
Stream Quality Improvement and Blending	Fire	Buildup of the flammable vapors	S = 2 F = 1 D = 1 **Total** = 2	no additional evidence is provided for the revenue loss

Table E-4. Economy based FMEA results for Petroleum Refinery Facility Continued…

Process Function	Hazard/Effects	Potential Causes/ Mechanisms of Failure	RPN for Economic	General Notes
Critical structure integrity	Damage to critical structures	Oil/byproducts detonation at Refinery plant	S = 1 F = 2 D = 1 **Total** = 2	Category I buildings are secure to at least 5.0 psig. Safe siting distance will be for 1.0 psig.
Makeup water pipeline	Loss of makeup water supply line	Oil/byproducts detonation at Refinery plant	S = 1 F = 2 D = 1 **Total** = 2	Would not affect NPP operation. Customer revenue would be lost until repaired.
Primary loop transport of process steam	Pipe Rupture after MSIV Damage to turbine building equipment, possibly safety power buses, depending on the plant	Operational vibration due to the detonation or explosion from the refinery plant	S = 1 F = 2 D = 1 **Total** = 2	More likely to affect the piping outside of the reboiler room leading to the customer. Prompt loss of heat load would occur.
Spent fuel storage (dry)	Damage to casks causes radiation leak	Oil/byproducts detonation at Refinery plant	S = 1 F = 2 D = 1 **Total** = 2	Dry casks are rated for fire protection.
Steam diversion load roughly 5% thermal	Prompt loss of thermal load	Oil/byproducts detonation at Refinery plant	S = 1 F = 2 D = 1 **Total** = 2	Not an issue unless the thermal diversion exceeds 30%.

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Appendix F: FMEA Results- Pulp and Paper Facility

The FMEA results for a pulp and paper facility are listed in the following tables.

Table F-1. Nuclear power plant based FMEA results for pulp and paper facility.

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for NPP	General Notes
Tertiary water intake contamination	Water supply contamination raises pH to a level that could harm NPP intake and other equipment. Water supply contamination clogs the water intake at the NPP	Chemical leak at paper facility.	S = 5 F = 3 D = 1 **Total = 15**	Severity is variable upon water supply source. A static source such as a lake or pond could present a hazard to the NPP if there is a leak at the pulp and paper facility. The severity could be reduced if source is a river where the pulp and paper facility is located downstream of the NPP.
Primary loop transport of process steam	Pipe Rupture after MSIV Damage to turbine building equipment, possibly safety power buses, depending on the plant	Explosion at paper facility	S = 1 F = 3 D = 2 **Total = 6**	Depends on placement. Assume sited at safe distance.
Spent fuel storage (dry)	Cask tip-over due to overpressure, cask structural degradation	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Possible damage to storage building, if used. Facility must have sufficient separation such that dry casks cannot be damaged. Multiple explosions have occurred at pulp and paper facilities, so frequency is a 3.
External Power	Loss of offsite power	Explosion at paper facility that reaches transmission towers	S = 1 F = 3 D = 1 **Total = 3**	Possible damage to transmission of offsite power. Facility must have sufficient separation such that offsite power cannot be disrupted. Multiple explosions have occurred at pulp and paper facilities, so frequency is a 3. Must also look at next-most fragile components beyond the transmission towers and auxiliary transformers to see if they are sited at critical distances.

Table F 1. Nuclear power plant based FMEA results for pulp and paper facility Continued…

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for NPP	General Notes
External Supply Tanks integrity	Damage to CST, other supply tanks	Explosion at paper facility that reaches NPP (or flying debris)	S = 1 F = 3 D = 1 **Total = 3**	Possible damage to storage tank. Facility must have sufficient separation such that dry casks cannot be damaged. Multiple explosions have occurred at pulp and paper facilities, so frequency is a 3.
Makeup water pipeline	Loss of makeup water supply to spray ponds/cooling towers due to damaged pipeline.	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	A sufficient supply of makeup water is necessary; a reduction may lead to inadequate cooling. It is presumed that the makeup water pipeline is either underground or enclosed. There is a potential risk of seismic disturbance to the pipeline leading to the ultimate heat sink.
Spray pond	Degradation of ultimate heat sink	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Debris clogging pond, possibly avoidable with proper placement.
Cooling tower pond	Degradation of ultimate heat sink	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Debris clogging pond, possibly avoidable with proper placement.
Non-Safety Service water pump house	Damage and/or loss of service water building and equipment.	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	NPP would need to shut down safely until repairs are made.
Forced air cooling for non-safety buildings	Damage and/or loss of NPP building HVAC equipment. Reactor building, admin building, etc.	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Can affect human operations. May have to shut down reactor.
NPP and paper administrative support	Damage to staffs' cars, office buildings and equipment	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	While not directly related to NPP safety, damage to support buildings can affect operations. Explosions have spread beyond the boundaries of the pulp and paper mills.
Physical protection	Damage to intrusion sensors, or triggering multiple false alarms, or empty guard posts due to evacuation.	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Lowered physical protection profile increases NPP vulnerability.

Table F-2. Industrial customer based FMEA results for pulp and paper facility

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for Industrial Plant**	**General Notes**
Multiple	Explosion	Multiple (including gas build up in pulp digester after loss of power)	S = 10 F = 3 D = 1 **Total = 30**	Explosions at pulp and paper mills require a shutdown of operations. In at least one instance an explosion led to a permanent shutdown.
Multiple	Entire facility shutdown	Fire	S = 5 F = 5 D = 1 **Total = 25**	There are many cases of fires occurring at pulp and paper facilities with a wide range of causes. Fires often lead to a shutdown of operation.
Delignification/washing/bleaching	Chemical Exposure	Leak of Chlorine Dioxide, black liquor, white liquor, etc.	S = 3 F = 4 D = 2 **Total = 24**	Multiple cases of chemical leaks at paper facilities have been recorded. Chlorine dioxide inhalation has led to death.
Delignification/washing/bleaching	Entire facility shutdown	Leak of Chlorine Dioxide, black liquor, white liquor, etc.	S = 3 F = 4 D = 2 **Total = 24**	Multiple cases of chemical leaks at paper facilities have been recorded.
Lime Kiln	Natural Gas Exposure	Pipe leak	S = 2 F = 1 D = 2 **Total = 4**	The lime kiln in current pulp and paper facilities requires the combustion of natural gas. It is possible that this can be eliminated with the use of electric heaters given power from the NPP.
Multiple	Explosion causing damage to nearby houses, other structures, or highway	Multiple (including gas build up in pulp digester after loss of power)	S = 3 F = 2 D = 1 **Total = 6**	Toxic debris and possible injuries. Explosions have spread beyond the boundaries of the pulp and paper mills.
Debarking/Chipping	Injury to personnel	Multiple (thrown wood chips, saw dust inhalation or eye contact)	S = 1 F = 4 D = 1 **Total = 4**	OSHA lists multiple accidents within the wood debarking and chipping process.
Bleaching	Chemical Exposure	Leak of hydrogen peroxide	S = 1 F = 1 D = 1 **Total = 1**	Hydrogen peroxide vapor can lead to eye and throat irritation, or difficulty breathing.

Table F-3. Public safety and perception based FMEA results for pulp and paper facility.

Process Function	Hazard/Effect	Potential Causes/ Mechanisms of Failure	RPN for NPP	General Notes
Delignification/washing	Contamination of water supply	Leak of Black Liquor, white liquor, etc.	S = 8 F = 4 D = 1 **Total = 32**	An accident occurred where black liquor leaked from a storage tank and drained into a river leading to the death of approximately 300kg fish.
Multiple	Damage to nearby houses, public buildings, and highway	Explosion at paper facility	S = 8 F = 3 D = 1 **Total = 24**	Toxic debris and possible injuries. Explosions have spread beyond the boundaries of the pulp and paper mills.
NPP & Pulp Facility administrative support	Damage to staffs' cars, office buildings and equipment	Explosion at paper facility	S = 8 F = 3 D = 1 **Total = 24**	Operations hindered until repairs are made.
Physical protection	Damage to intrusion sensors, or triggering multiple false alarms	Explosion at paper facility	S = 8 F = 3 D = 1 **Total = 24**	Lowered physical protection profile increases NPP vulnerability physically and in the eyes of the public.
Delignification/washing/bleaching	Evacuation	Explosion or leak of chlorine dioxide, black liquor, white liquor, etc.	S = 8 F = 2 D = 1 **Total = 16**	A leak that leads to an evacuation would likely have vastly negative effect on public perception if the leak is near an NPP.

Table F-4. Economy based FMEA results for pulp and paper facility.

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for NPP**	**General Notes**
Bleaching	Toxic exposure to pulp and paper mill employees	Leak of Chlorine Dioxide	S = 2 F = 3 D = 3 **Total = 24**	Chlorine dioxide inhalation has led to death.
Tertiary water intake contamination	Contamination of water supply	Leak of Black Liquor, white liquor, etc.	S = 5 F = 3 D = 1 **Total = 15**	Severity is variable upon water supply source. A static source such as a lake or pond could present a hazard to the NPP if there is a leak at the pulp and paper facility. The severity could be reduced if source is a river where the pulp and paper facility is located downstream of the NPP.
Multiple	Explosion causing damage to nearby houses, other structures, or highway. Potential toxic exposure to public.	Multiple (including gas build up in pulp digester after loss of power)	S = 4 F = 3 D = 1 **Total = 12**	Toxic debris and possible injuries. Explosions have spread beyond the boundaries of the pulp and paper mills.
NPP & paper administrative support	Damage to staffs' cars, office buildings and equipment	Explosion at paper facility	S = 2 F = 3 D = 1 **Total = 6**	Assumes safe siting distance for the NPP staff but uses severity for pulp and paper staff.
External supply tanks integrity	Damage to CST, other supply tanks	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 6**	Possible damage to storage tank. Facility must have sufficient separation such that dry casks cannot be damaged. Multiple explosions have occurred at pulp and paper facilities, so frequency is a 3.
Delignification/washing	Toxic exposure to pulp and paper mill employees	Leak of Black Liquor	S = 2 F = 3 D = 1 **Total = 6**	Black liquor exposure may cause burns to the skin, eyes, lungs, and upper gastrointestinal tract.
Debarking/Chipping	Injury to personnel	Wood thrown out or workers caught	S = 2 F = 2 D = 1 **Total = 4**	OSHA lists multiple accidents within the wood debarking and chipping process, but minor effects.
Primary loop transport of process steam	Pipe Rupture after MSIV Damage to turbine building equipment, possibly safety power buses, depending on the plant	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Assumes safe siting distance. Primary loop is essential for heat source of power cycle. No power generation for NPP leads to no basic commodity generation.

Table F 4. Economy based FMEA results for pulp and paper facility Continued …

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for NPP**	**General Notes**
Makeup water pipeline	Loss of makeup water supply line	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Assumes safe siting distance. Makeup water required for NPP safety, cooling system, would require immediate attention and pause of normal operations.
Non-Safety Service water pump house	Damage and/or loss of service water building and equipment.	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Assumes safe siting distance. NPP would need to shut down safely until repairs are made.
Forced air cooling for non-safety buildings	Loss of HVAC equipment	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Assumes safe siting distance.
External Power	Loss of offsite power	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Assumes safe siting distance. Dependent on emergency power system, how long emergency power is required.
Spray pond	Degradation of ultimate heat sink	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Debris clogging pond, possibly avoidable with proper placement.
Cooling tower pond	Degradation of ultimate heat sink	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Debris clogging pond, possibly avoidable with proper placement.
Physical protection	Damage to intrusion sensors, or triggering multiple false alarms	Explosion at paper facility	S = 1 F = 3 D = 1 **Total = 3**	Assumes safe siting distance.

Appendix G: Industrial Products and Feedstock Physical Properties for Safety Analysis Supporting Information

Table G-1. Lists of flammable and detonable products and feedstocks in methanol plant [2].

	Flash Points	Auto-ignition Temperature	Flammability Limit
Feedstocks			
Hydrogen	-250°C	400°C	4%-75%
Natural Gas	-161.5°C	537°C	4%-15%
Products			
Methanol	11°C	464°C	6%-37%

Table G-2. Lists of flammable and detonable products and feedstocks in Synthetic Fuel Plant.

	Flash Points	Auto-ignition Temperature	Flammability Limit
Feedstocks			
Hydrogen	-250°C	400°C	4%-75%
Products			
Diesel	>52°C	~257°C	0.60%-6.50%
Jet Fuel	>38°C	~250°C	0.60%-6.00%
Naphtha	>-22°C	~293°C	1.20%-7.00%
Intermediate stream			
Carbon Monoxide	N/A	607°C	10.9%-74.2%

Table G-3. Lists of flammable and detonable products and feedstocks in Refinery Plant.

Streams	Flash Points	Auto-ignition Temperature	Flammability limit
Feedstocks			
Crude Oil	>60°C	N/A	0.70%-7.00%
Hydrogen	-250°C	400°C	4%-75%
Natural Gas	-161.5°C	537°C	4%-15%
Products			
Gasoline	-40°C	>250°C	1.40%-7.60%

Streams	Flash Points	Auto-ignition Temperature	Flammability limit
Liquefied petroleum gas (LPG)	<-40°C	>450°C	2%-11%
Propane	-104°C	450°C	2%
Butane	-60°C	365°C	2%-8%
Jet Fuel	>38°C	~250°C	0.60%-6.00%
Diesel	>52°C	~257°C	0.60%-6.50%
Sulfur	188°C	255°C	N/A
Intermediate streams			
Refinery fuel gas	-188°C	472°C	4%-17%
Naphtha	>-22°C	~293°C	1.20%-7.00%
Atmospheric gasoil	88-99°C	~210°C	1%-6%
Vacuum gasoil	88-99°C	~210°C	1%-6%
Vacuum residue	>100°C	~250°C	N/A. Explosion lower limit =1%-6%
Hydrogen sulfide (H2S)	−82.4 °C	270°C	N/A

Table G-4. Lists of flammable and detonable products and feedstocks in Refinery Plant.

Streams	Flash Points	Auto-ignition Temperature	Flammability upper limit
Feedstocks			
Wood chips	-188°C	537°C	4%-15%
Black, viscous liquid	>60.5°C	>407°C	0.1%-3.0%
Products			
Turpentine	35°C	253°C	0.80%

Table G-5. Lists of toxic products and feedstocks in Methanol Plant

Products	**TWA Toxicity**	**STEL**	**Oral Toxicity**	**Dermal Toxicity**
Methanol	ATE= 100 mg/kg	N/A	ATE = 100 mg/kg	ATE = 300 mg/kg

Table G-6. Lists of toxic products and feedstocks in Synthetic Fuel Plant

	TWA Toxicity	**STEL**	**Oral Toxicity**	**Dermal Toxicity**
Products				
Diesel	N/A	N/A	ATE >5,000 mg/kg	ATE >5,000 mg/kg
Jet Fuel	N/A	N/A	ATE >5,000 mg/kg (LD50)	ATE >2,000 mg/kg (LD50)
Naphtha	N/A	N/A	ATE >5,000 mg/kg	ATE >3,350 mg/kg
Intermediate stream				
Carbon Monoxide	25 ppm (8 hours)-ACGIH 35 ppm (10 hours)-NISOH REL 50 ppm (8 hours)-OSHA PEL	N/A	ATE=1880 ppm	N/A

Table G-7. Lists of toxic products and feedstocks in Refinery Plant.

Streams	TWA Toxicity	STEL	Oral Toxicity	Dermal Toxicity
Feedstocks				
Crude Oil	2,000 mg/m3	N/A	ATE >5,000 mg/m3	ATE >2,000 mg/m3
Products				
Gasoline	100 mg/m3	200 mg/m3	N/A	N/A
Propane	1,800 mg/m3	N/A	N/A	N/A
Butane	N/A	1,000 ppm	N/A	N/A
Jet Fuel	N/A	N/A	ATE >5,000 mg/kg (LD50)	ATE >2,000 mg/kg (LD50)
Diesel	N/A	N/A	ATE >5,000 mg/kg	ATE >5,000 mg/kg
Sulfur	N/A	N/A	ATE >2,000 mg/kg	ATE >2,000 mg/kg
Intermediate streams				
Naphtha	N/A	N/A	ATE >5,000 mg/kg	ATE >3,350 mg/kg
Atmospheric gasoil	N/A	N/A	ATE >5,000 mg/kg	ATE >2,000 mg/kg
Vacuum gasoil	N/A	N/A	ATE >5,000 mg/kg	ATE >2,000 mg/kg
Vacuum residue	N/A	N/A	ATE >5,000 mg/kg	ATE >2,000 mg/kg
Hydrogen sulfide (H2S)	5 ppm (7 mg/m^3)	10 ppm (14 mg/m^3)	N/A	N/A
Hydrofluoric acid	N/A	N/A	ATE = 5-50 mg/kg	ATE <50 mg/kg

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Appendix H: Gas Component Leakage Frequencies for Safety Analysis Supporting Information

The leak frequencies per year of gas components were calculated in a report for the hydrogen facility analyses by SNL for Reference [1]. Both generic gas and hydrogen-specific components leakage frequencies are listed in this appendix. The hydrogen leak rates were calculated using a Bayesian statistical analysis that combined leak events from non-hydrogen sources that are representative of hydrogen components with the limited data for leak events from hydrogen-specific components. The resulting component leak frequencies are documented as a function of normalized leak size. Further information is included in [1].

Table H-1. Component Leak Frequencies

Component	**Fractional Leak Size**	**Generic Leak Frequencies (/y)**				**Hydrogen Leak Frequencies (/y)**			
		Mean	**5th**	**Median**	**95th**	**Mean**	**5th**	**Median**	**95th**
Compressor	0.0001	6.0E+00	2.5E-01	2.2E+00	1.9E+01	1.0E-01	5.9E-02	1.0E-01	1.6E-01
	0.001	1.8E-01	2.1E-02	1.1E-01	5.4E-01	1.9E-02	6.8E-03	1.7E-02	3.8E-02
	0.01	9.2E-03	1.0E-03	5.2E-03	2.7E-02	6.3E-03	1.2E-03	4.6E-03	1.7E-02
	0.1	3.4E-04	8.2E-05	2.6E-04	8.0E-04	2.0E-04	4.6E-05	1.5E-04	4.9E-04
	1	3.3E-05	1.7E-06	1.2E-05	9.3E-05	3.2E-05	2.0E-06	1.5E-05	1.0E-04
Cylinder	0.0001	1.5E+00	6.6E-02	6.6E-01	5.3E+00	1.6E-06	3.5E-07	1.4E-06	3.4E-06
	0.001	3.4E-02	3.4E-03	2.0E-02	1.0E-01	1.3E-06	3.7E-07	1.2E-06	2.8E-06
	0.01	8.4E-04	1.6E-04	6.4E-04	2.1E-03	9.0E-07	2.6E-07	7.9E-07	1.9E-06
	0.1	2.5E-05	6.6E-06	1.9E-05	5.9E-05	5.2E-07	1.6E-07	4.5E-07	1.1E-06
	1	7.6E-07	1.9E-07	6.1E-07	1.8E-06	2.7E-07	8.1E-08	2.3E-07	6.0E-07
Filter	0.0001	6.9E-02	3.4E-04	5.3E-03	8.4E-02	NA	NA	NA	NA
	0.001	1.4E-02	6.2E-04	5.1E-03	4.1E-02	NA	NA	NA	NA
	0.01	1.6E-02	6.0E-04	4.8E-03	3.9E-02	NA	NA	NA	NA
	0.1	6.1E-03	1.4E-03	4.6E-03	1.5E-02	NA	NA	NA	NA
	1	6.4E-03	1.2E-03	4.4E-03	1.6E-02	NA	NA	NA	NA
Flange	0.0001	6.5E-02	1.7E-03	2.0E-02	2.3E-01	NA	NA	NA	NA
	0.001	4.3E-03	3.4E-04	2.2E-03	1.4E-02	NA	NA	NA	NA
	0.01	3.5E-03	8.4E-06	2.4E-04	7.0E-03	NA	NA	NA	NA
	0.1	3.5E-05	8.3E-06	2.7E-05	8.6E-05	NA	NA	NA	NA
	1	1.9E-05	1.9E-07	2.9E-06	4.6E-05	NA	NA	NA	NA
Hose	0.0001	2.8E+01	1.6E+00	1.3E+01	9.4E+01	6.1E-04	2.9E-04	5.8E-04	1.0E-03

Component	Fractional Leak Size	Generic Leak Frequencies (/y)				Hydrogen Leak Frequencies (/y)			
		Mean	**5th**	**Median**	**95th**	**Mean**	**5th**	**Median**	**95th**
	0.001	2.2E+00	2.9E-01	1.4E+00	6.4E+00	2.2E-04	6.6E-05	2.0E-04	4.5E-04
	0.01	2.1E-01	4.3E-02	1.6E-01	5.2E-01	1.8E-04	5.3E-05	1.6E-04	3.8E-04
	0.1	2.2E-02	6.0E-03	1.7E-02	5.3E-02	1.7E-04	5.1E-05	1.5E-04	3.4E-04
	1	5.6E-03	1.9E-04	2.0E-03	1.8E-02	8.2E-05	9.6E-06	6.2E-05	2.2E-04
Joint	0.0001	1.3E+00	7.0E-02	5.3E-01	4.6E+00	3.6E-05	2.3E-05	3.5E-05	5.1E-05
	0.001	1.7E-01	2.1E-02	1.0E-01	5.2E-01	5.4E-06	8.4E-07	4.7E-06	1.2E-05
	0.01	3.3E-02	4.2E-03	1.8E-02	9.3E-02	8.5E-06	2.9E-06	7.9E-06	1.6E-05
	0.1	4.1E-03	1.3E-03	3.5E-03	8.6E-03	8.3E-06	2.4E-06	7.5E-06	1.7E-05
	1	8.2E-04	2.3E-04	6.3E-04	1.9E-03	7.2E-06	1.8E-06	6.4E-06	1.5E-05
Pipe	0.0001	5.9E-04	7.1E-05	3.6E-04	1.8E-03	9.5E-06	2.1E-06	8.0E-06	2.2E-05
	0.001	8.6E-05	1.7E-05	6.2E-05	2.2E-04	4.5E-06	1.1E-06	3.7E-06	1.1E-05
	0.01	3.5E-05	9.1E-07	1.1E-05	1.3E-04	1.7E-06	9.9E-08	9.6E-07	5.9E-06
	0.1	4.7E-06	2.3E-07	1.9E-06	1.6E-05	8.4E-07	5.8E-08	4.6E-07	2.9E-06
	1	3.7E-06	1.0E-08	3.2E-07	1.0E-05	5.3E-07	5.5E-09	1.5E-07	2.3E-06
Pump	0.0001	3.9E-02	2.4E-03	1.8E-02	1.3E-01	NA	NA	NA	NA
	0.001	6.5E-03	8.5E-04	4.2E-03	1.9E-02	NA	NA	NA	NA
	0.01	2.5E-03	9.9E-05	9.5E-04	8.3E-03	NA	NA	NA	NA
	0.1	2.8E-04	7.2E-05	2.1E-04	6.7E-04	NA	NA	NA	NA
	1	1.2E-04	5.4E-06	4.9E-05	4.1E-04	NA	NA	NA	NA
Valve	0.0001	2.0E-02	2.2E-03	1.2E-02	6.4E-02	2.9E-03	1.9E-03	2.9E-03	4.2E-03
	0.001	2.8E-03	5.0E-04	1.9E-03	7.5E-03	6.3E-04	2.7E-04	5.9E-04	1.1E-03
	0.01	1.2E-03	2.6E-05	3.1E-04	4.0E-03	8.5E-05	6.6E-06	5.4E-05	2.7E-04
	0.1	6.4E-05	1.8E-05	5.3E-05	1.5E-04	3.0E-05	8.7E-06	2.5E-05	6.7E-05
	1	2.6E-05	8.3E-07	8.5E-06	9.1E-05	1.1E-05	4.7E-07	4.8E-06	4.2E-05