INL/RPT-23-74319

Revision 0

Light Water Reactor Sustainability Program

Flexible Plant Operation and Generation

Expansion of Hazards and Probabilistic Risk Assessments of a Light-Water Reactor Coupled with Electrolysis Hydrogen Production Plants

August 2023

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Office of Nuclear Energy

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Expansion of Hazards and Probabilistic Risk Assessments of a Light-Water Reactor Coupled with Electrolysis Hydrogen Production Plants

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EXECUTIVE SUMMARY

This report builds upon the body of work sponsored by the Department of Energy (DOE) Light-Water Reactor Sustainability (LWRS) Flexible Power Operation and Generation (FPOG) program that presented generic probabilistic risk assessments (PRAs) for the addition of a heat extraction system (HES) to light-water reactors [1] to support the co-location of a high temperature hydrogen electrolysis facility (HTEF). Probabilistic and deterministic hazards assessments and risk analyses are leveraged throughout this report. Several improvements and new analyses are included in this report. First, higher amounts of detail in the specifications of the generic HTEFs are used to produce scaled results for a 100, 500, and 1000 MW nominal hydrogen production facility. An additional hazard assessment of 1000 kg of hydrogen storage is performed. The facility hazards and footprint are assessed to determine the safe distance required for placement near the nuclear power plant (NPP). Second, specific designs for corresponding HESs for the different levels of support required by the HTEFs are analyzed in the PRA model. Third, a hazards analysis of the specified HTEFs leads not only to effects of the quantified risk assessment for the NPP, but also qualitative hazards assessment for the community. Finally, a seismic analysis and a high winds analysis have each been added to the PRA.

The results investigate the applicability of the potential licensing approaches which do not require a full United States (U.S.) Nuclear Regulatory Commission (NRC) licensing review. The PRAs are generic and include listed assumptions. The HTEF design built for this project has further eliminated many conservative assumptions from the prior PRAs in this series [1]. The PRA results indicate that the 10 CFR 50.59 licensing approach is justified due to the minimal increase in initiating event frequencies for all design basis accidents, with none exceeding 7.7%. The PRA results for core damage frequency and large early release frequency support the use of NRC Regulation Guide 1.174 as further risk information that supports a change without a full licensing amendment review. The hazard analyses and PRA confirm the need for engineered blast barriers of storage tanks and the common production header leaving the HTEF. The hazards analyses and PRA also confirm with high confidence that using the assumptions of design in this report that the safety case for licensing an HES addition and an HTEF sited with its unprotected high-pressure stage components 187 meters from the NPP's transmission towers (the most fragile structure, system, and component) is strong.

ACKNOWLEDGEMENTS

The authors of this report would like to thank Austin Glover and the HyRAM+ team at Sandia National Laboratories for outstanding support in the hydrogen plant safety analysis leak rates, frequencies, and overpressure estimates. We also would like to thank Tyler Westover for tremendous support in the design of and interface with solid oxide electrolysis cell (SOEC) systems and the vendors of SOEC systems. Jack Cadogan and Jason Remer of whom lead the LWRS Hydrogen Research Regulatory Review Group (H3RG) were invaluable in providing technical and utility perspectives. We also thank Alan Wilson, Quentin Ratay, and the rest of the Sargent and Lundy engineering team for their outstanding support in providing generic designs of HTEF configurations and the necessary footprints, pipe lengths, volumes, and more that were necessary to take the hydrogen plant safety analysis, and therefore the more precise hazards analysis to the NPP, to the next level.

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ACRONYMS

AFW	auxiliary feedwater
ATWS	anticipated transient without scram
Bauwens	Bauwens-Dorofeev hydrogen jet leak detonation consequence methodology
BWR	boiling-water reactor
CCF	common cause failures
CDF	core damage frequency
CPH	common production header (of the HTEFs)
CST	condensate storage tanks
DBA	design basis accidents
DOE	U.S. Department of Energy
FMEA	failure modes and effects analysis
H3RG	Hydrogen Research Regulatory Review Group
HES	heat extraction system
HPI	high-pressure injection
HTEF	high-temperature electrolysis facility
HTF	heat-transfer fluid
HRA	Human reliability analysis
IE	initiating event
IPEEE	individual plant examination of external events
LAR	licensing amendment review
LERF	large early release frequency
LOOP	loss of offsite power
LPI	low-pressure injection
LWR	light-water reactor
LWRS	Light Water Reactor Sustainability program
MCA	maximum credible accident
MSIV	main steam isolation valves
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
P&ID	piping and instrumentation diagram
PCS	power conversion system
PRA	probabilistic risk assessment
PSF	performance shaping factors (used in SPAR-H)

PWR	pressurized-water reactor
RCP	reactor coolant pump
RPN	risk priority number
RPS	reactor protection system
RWST	refueling water storage tanks
S&L	Sargent and Lundy company
SAPHIRE	Systems Analysis Programs for Hands-on Integrated Reliability Evaluations
SBO	station blackout
SME	subject matter expert
SNL	Sandia National Laboratories
SPAR-H	Standardized Plant Analysis Risk HRA
SSC	structures, systems, and components

Flexible Plant Operation and Generation

Expansion of Hazards and Probabilistic Risk Assessments of a Light-Water Reactor Coupled with Electrolysis Hydrogen Production Plants

1. INTRODUCTION

This report consists of a collection of hazard analyses that support the modifications of the nuclear power plant (NPP) that are necessary to support the placement of a co-located high temperature electrolysis hydrogen production facility (HTEF). The identified hazards provide input to the probabilistic risk assessment (PRA) model of the generic NPP and HTEF facilities. The fragility of the NPP structures, systems, and components (SSCs) combined with deterministic consequence analysis were used to risk-inform the safe separation distance of the HTEF from the NPP's most fragile SSC, the switchyard transmission tower. A similar deterministic approach was also used to estimate the separation distance by using the U.S. Nuclear Regulatory Commission's (NRC) Regulation Guide 1.91 [11]. Modifications to the NPP and external hazards from the HTEF were added to existing PRA models. Both the deterministic and probabilistic results support the licensing case for the proposed changes to the NPP and safe siting distance of the HTEF.

1.1 Why Nuclear-Supported Hydrogen Generation?

The emerging gap between the growth of non-dispatchable renewable energy generation and lagging clean energy storage continues to contribute to the unproductive expansion of time-of-day excess clean energy generation. The overlapping impact of 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. During these times, nuclear could flexibly produce real-time usable or storable clean energy to decarbonizing functions across the power, industrial, and transportation sectors. Specifically, hydrogen by electrolysis as a flexible energy stream from the existing nuclear fleet has the potential to favorably influence these sectors as a storage medium and energy carrier for excess intermittent carbon-free generation.

In recent years, the development of water-splitting electrolysis systems has dramatically accelerated as the interest in clean hydrogen production and global decarbonization of transportation, industrial, and other sectors have increased. Electrolyzed hydrogen produced by renewables and low-temperature electrolysis (LTE) is already emerging as a near-term clean stored-energy carrier. This clean storage capability will likely be an important and diversified national complement to limited renewable electricity storage via Lithium-Ion batteries and other emerging storage technologies. High-temperature steam electrolysis (HTE) systems achieve relatively higher overall system efficiencies compared to LTE. Nuclear generators are unique in their capability to deliver both clean electrical and heat energy output—the two components needed to produce clean, high-efficiency hydrogen by HTE, shown in Figure 1-1.

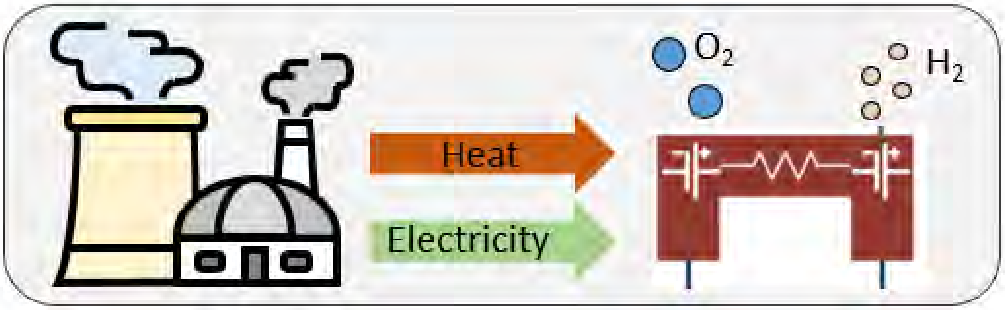

Figure 1-1. Nuclear provides heat and electricity for high-temperature electrolysis.

The U.S. Department of Energy (DOE) support under the Light Water Reactor Sustainability (LWRS) Flexible Power Operations and Generation (FPOG) Pathway at Idaho National Laboratory (INL) is accelerating key technology development in this area. The current LWRS R&D focus regarding implementation of integrated hydrogen generation at nuclear facilities is being addressed through exploration of practical pre-conceptual designs, pilot hydrogen projects, and development of likely licensing success paths consistent with the United States Nuclear Regulatory Commission (NRC) requirements.

For the suggested change to the light-water reactor (LWR) design and operation to be approved, the NRC requires a demonstration that the nuclear power plant (NPP) safety will not be adversely affected. A probabilistic risk assessment (PRA) is used to risk inform the decision for change acceptance by the NRC. 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 quantitative PRA results are compared to 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.

1.2 PRA Role in Safety and Licensing of Nuclear Power Plant Modifications

An LWR PRA is broken into three levels, the first of which answers the risk-informed questions present in 10 CFR 50.59, "Changes, Tests and Experiments" [2]. These questions concentrate on the changes in initiating event frequency of design basis events caused by the proposed modifications. The Level 1 PRA also determines overall core damage frequency (CDF) and large early release frequency (LERF) which are metrics used in the risk-informed support of changes to licensing basis, NRC Regulation Guide 1.174 [3]. RG 1.174 can be used as further supporting information to back up decisions made in the 10 CFR 50,59 process.

A Level 1 PRA estimates the frequency per year of CDF events. This is done using two types of logical structures—event trees (ETs) and fault trees (FTs). An ET represents the possible pathways that can occur due to an undesired outcome. The initial undesired event is called an initiating event (IE). After the IE, the ET uses FT model results representing responding systems that prevent core damage. These FTs are the top events of the ET. The ET sequence of events results in end states indicative of the reactor state. The end state of interest here is core damage. All basic events of component or human action failures have associated probabilities of failure that are used in relation to one another as defined by the logic trees. The sum of the probabilities associated with all the sequences leading to the core damage end state represent the CDF.

Top-down methods are typically used to define IE frequencies by using data of recorded events to calculate the event frequency.

The probability of failure for FT top events are calculated using a bottom-up method. Bottom-up methods rely on knowing the exact system componentry and controls that are then translated into an 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 a failure event in the 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. OBJECTIVE

The objective of this document is to further refine and expand upon the initial PRA [1]. This PRA includes both boiling-water reactor (BWR) and pressurized-water reactor (PWR) generic models to provide examples for starting a site-specific PRA. These PRAs include the risk assessment of proposed design options for thermal transfer, direct electrical transfer, and three sizes of hydrogen electrolysis facilities (100 MW, 500 MW, and 1000 MW). The PRA has also expanded to include defined generic hydrogen plant facilities for the three sizes of hydrogen facilities, hazards analysis of 1000 kg of hydrogen storage, effects from seismic and wind events, and hazards analysis of the hydrogen plant as they affect the local community and economy of the operating utility.

3. PROJECT SCOPE

The scope of this report is a Level 1 PRA that models the design basis IE frequencies and risk of core damage by quantifying the CDF associated with modifying the LWR to remove heat from the process steam and provide this heat and a dedicated electrical connection from the LWR to a high temperature electrolysis facility (HTEF). Within the PRA, the HTEF and its electrical connection to the LWR is treated as both a potential internal and external event hazard upon the LWR. The IE frequencies associated with the addition of the proposed LWR heat extraction systems (HES) and the HTEF are compared against the guidelines set in 10 CFR 50.59 and the CDF and LERF calculated from the PRA are compared against the guidelines set in RG 1.174. Recommendations for the applicability of the results to this licensing path are given in this report.

The scope further uses the detailed HTEF facilities at 100 MW, 500 MW, and 1000 MW to perform a hazards analysis and facility siting analysis. The hazards analyses for these HTEFs provide quantitative input to the PRA of the NPP and qualitative results are used to assess the risk to the local community and the economics of the NPP. Standoff distances are assessed, and standoff distances are provided for acceptable risk to the NPP.

Seismic and wind events are assessed to determine if any effects on the HTEF will affect the NPP.

Storage of hydrogen at 1000 kg is also assessed, and a standoff distance is provided for acceptable risk to the NPP.

4. SPECIFICATIONS OF THE SUPPORTED HYDROGEN FACILITY

Prior reports in this series [1] assumed a high-temperature, high-pressure electrolysis module was the bounding accident for HTEF. The modeling assumption was for a single macro-module of the size of the HTEF. While this was a conservative start and provided initial positive answers to the licensing questions in 10 CFR 50.59 at a 500 m standoff distance, it was desired to go farther in generic specification to refine the hazards analysis and the PRA and to determine the effects of larger HTEF capacities and facility footprints on their placement next to the NPP. The architectural engineering firm of Sargent & Lundy (S&L) was contracted to help develop a generic HTEF for use in this updated PRA.

The sizes of the HTEFs proposed are 100 MW, 500 MW, and 1000 MW nominal (MW_e) energy rating. The reference NPP is a 3,650 MW thermal (MW_t) plant that provides 1,200 MW electric power, about 33% efficiency. The power ratings of the HTEF and the NPP, along with the steam extraction percentage of the HES and location of the HES steam tap for analyzed sizes of HTEFs are summarized in Table 5-1.

S&L specified a 100 MW_{nom} HTEF for this report in a report to the INL PRA team [4]. The 100 MW_{nom} HTEF shown in Figure 4-1 consists of 1.8 MW solid oxide electrolyzer cell (SOEC) modules each within 8 ft × 52 ft vented containers. The SOEC modules are arranged in 10 MW blocks consisting of six 1.8 MW modules each. There were two layouts provided, one in a rectangular facility layout and one in a square facility layout. The different layouts were requested to provide flexibility in siting considerations. The steam from the NPP is delivered to the SOECs from a common header. After the steam is used it is condensed and run through a demineralized water plant in the balance of plant area. The demineralized water is returned to the NPP for use in the reboiler to again become the steam supply for the HTEF. The rectangular layout is shown in Figure 4-1. The low pressure (5 psi maximum) hydrogen outputs of the SOEC modules are combined in a module block header (shown in red). Each SOEC module has a safety valve to isolate its hydrogen output from the other modules in case of a leak. The hydrogen is run through a compression stage at the end of each module block. The medium pressure (300 psi maximum) header collects the hydrogen compressed from the module blocks and delivers it to the final compression stage (1500 psi) for pipeline transportation and storage. Note that safety valves isolate sections of the piping to help prevent cascading leaks and other accidents.

The INL team specified the 500 MW HTEF in consultation with S&L for architectural engineering and Sandia National Laboratories (SNL) for accident consequences of the design. The most important aspect of the 500 MW design is that the piping is kept at the same diameters and volumes of the 100 MW design until the facility output pipes are combined in an underground header immediately offsite of the facility for transport to storage. This means that the same standoff distances used in the 100 MW HTEF design can be used in both the 500 MW and 1000 MW designs. The same 10 MW SOEC module blocks design is used for the 500 MW HTEF except that SOEC module blocks are stacked to a second level to save HTEF facility footprint size excluding two module blocks, which are at a single level (Figure 4-2). The 10 MW modules are kept in 100 MW piping configurations to keep the pipe sizes and hydrogen volumes the same as the 100 MW HTEF. The five output pipes are combined in a header underground after the high-pressure compression stage to keep the maximum hydrogen detonation accident consequence at the same level as the 100 MW design. The 500 MW footprint is shown in Figure 4-2.

The 1000 MW HTEF consists of two 500 MW HTEFs feeding one transport pipeline.

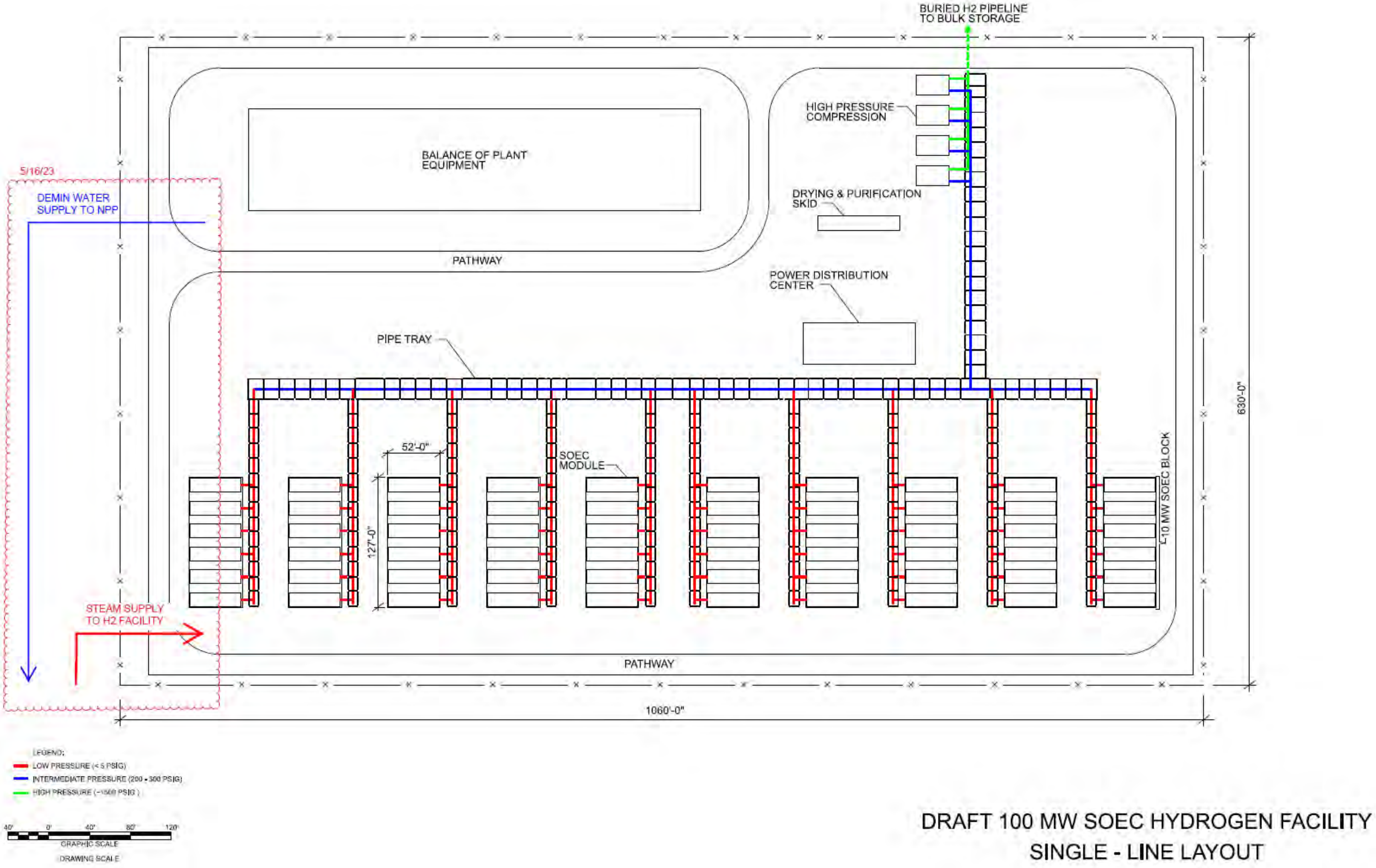

Figure 4-1. 100 MW HTEF Design Layout.

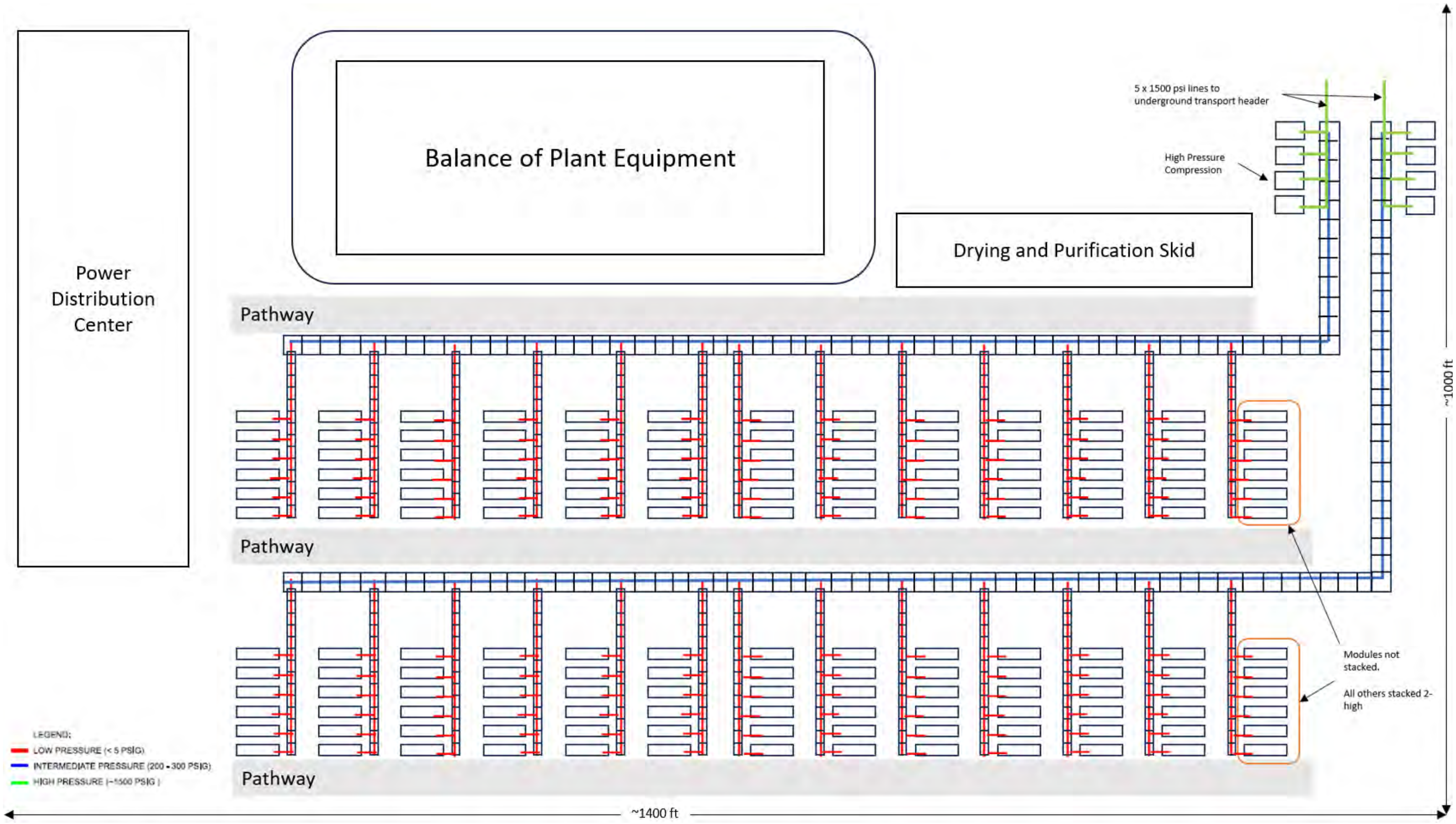

Figure 4-2. 500 MW HTEF Design Layout.

5. NUCLEAR POWER PLANT MODIFICATIONS FOR A HYDROGEN CUSTOMER

There are two NPP system modifications proposed. The first is adding the HES to extract thermal power and provide it to the HTEF. The second is adding components to the switchyard necessary to provide direct electrical coupling to the HTEF.

5.1 Nuclear Power Plant with Heat Extraction System and Collocated High-Temperature Electrolysis Facility System Description

There are three conceptual designs proposed for the HES. All designs utilize a single stage reboiler(s) that are located adjacent to the turbine building [5] [6]. The difference between the designs is the difference in the location and number of the steam taps. S&L recommended that the 100 and 500 MW_{nom} HTEFs use a steam tap after the high pressure (HP) turbine and that a 1000 MW_{nom} HTEF HES uses a steam tap before the HP turbine [5]. The power ratings for the proposed HTEFs and the main steam extraction percentages are listed in Table 5-1. A description of each design is provided below.

Site-specific HES design iterations should follow similar probabilistic analysis presented in this report to maintain the minimal increase in design basis accident (DBA) IE frequencies required by 10 CFR 50.59 (Section 9.1).

Table 5-1. Power ratings for proposed HTEFs and NPP.

Proposed HTEF			**Reference Nuclear Power Plant**		
MW_{nom}	**MW_e**	**MW_t**	**Full MW_t**	**% Steam Extraction (MW$_t$ HTEF/ MW$_t$ NPP)**	**HES Steam Tap**
100	100	25	3650	0.68%	After first turbine
500	500	105	3650	2.88%	After first turbine
1000	1000	205	3650	5.62%	Before the first turbine

5.1.1 100 MW_{nom} High-Temperature Electrolysis Facility Heat Extraction System Design with 25 MW_t Steam Delivery

The HES for HTEFs up to 500 MW_{nom} is shown in Figure 5-1. The modifications required of the NPP are a steam tap prior to the HP turbine, a control valve system controlled by the NPP, steam piping leading to a building adjacent to the turbine building, steam connection to a reboiler fed by deionized (DI) water from the HTEF, steam piping leading to the HTEF, and DI water piping returning from the HTEF [5]. The reboiler is placed in its own building outside of the turbine building for space consideration, isolation for maintenance, and to protect the turbine building equipment.

The modifications required of the NPP for a 100 MW_{nom} HTEF are a steam tap after the HP turbine, a control valve system controlled by the NPP, steam piping leading to a building adjacent to the turbine building, steam connection to a reboiler fed by DI water from the HTEF, steam piping leading to the HTEF, and DI water piping returning from the HTEF [5].

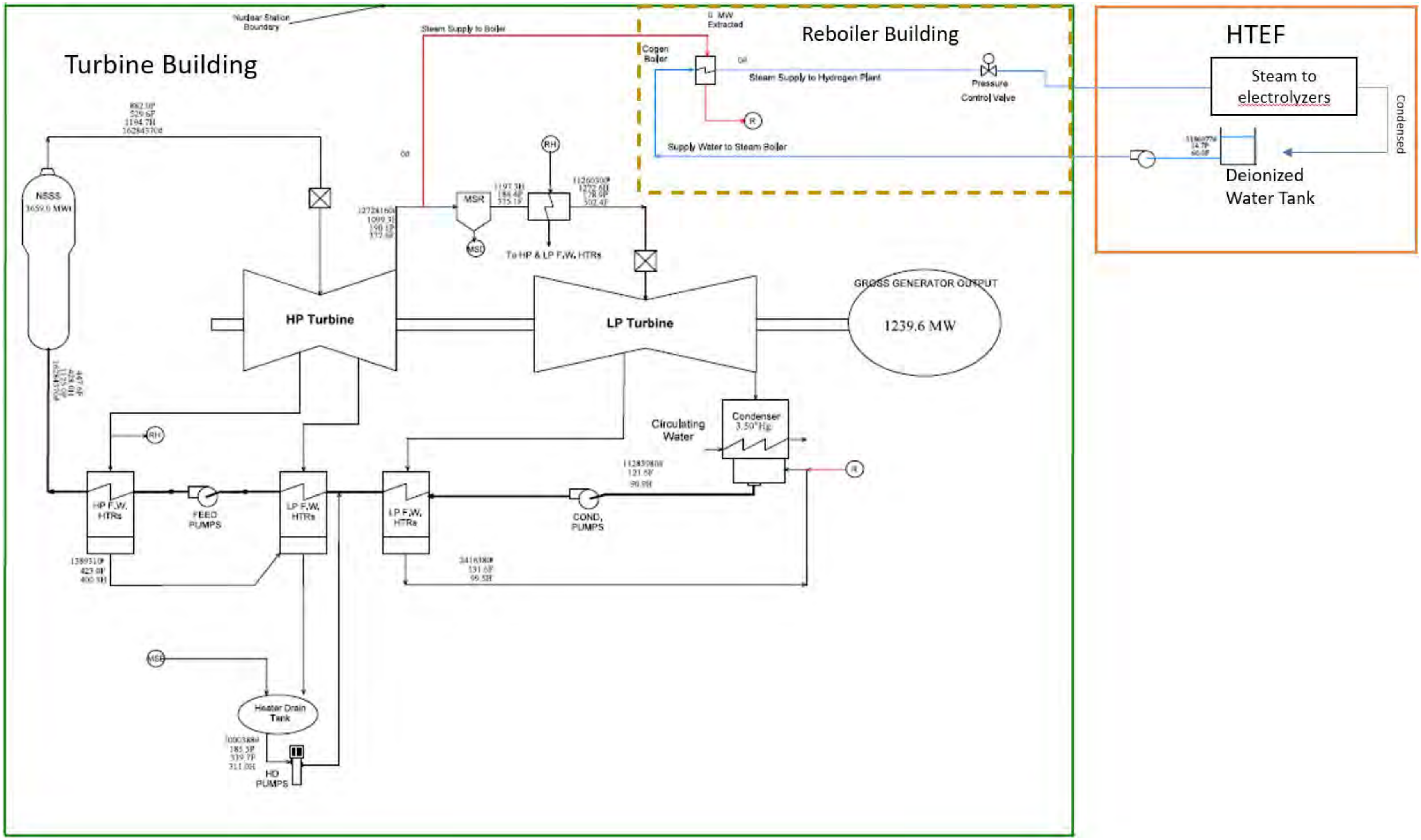

Figure 5-1. Model drawing of 100 MW_{nom} HES.

The PRA requires a specification of the components added as a part of the modification of the NPP that affect the safety of the power plant. The diagram of a steam extraction line downstream from the HP turbine leading to the reboiler is shown in Figure 5-2 [5]. The diameter of the piping for the 100 MW_{nom} HTEF is 10 in., 240 ft in length. This results in a maximum steam velocity of ~120 ft/sec. P1, P2, P3, and P5 are each 10-ft long with two 90-degree elbows. P4 is 200-ft long. A design pressure of 250 psig and design temperature of 400°F is assumed. J1 is the tap from the main steam, J2 and J5 are gate valves that are normally open in HES operation. J3 is a flow control valve with a constant pressure drop of 20 psig, assumed to have no flow-stopping capability. J4 is a stop check 90-degrees globe valve. J6 is the inlet to the reboiler. The pipe's insulation is assumed 4.5-in.-thick Calcium Silicate. The piping is located inside the turbine building, with an assumed indoor temperature of 70°F and air velocity of 0.1 ft/sec [5].

Since a failure in steam extraction lines up to, and including, the reboilers will affect the main steam line of the NPP and lead to an increased risk to the NPP, an FT for the line is developed, as shown in Figure 7-17.

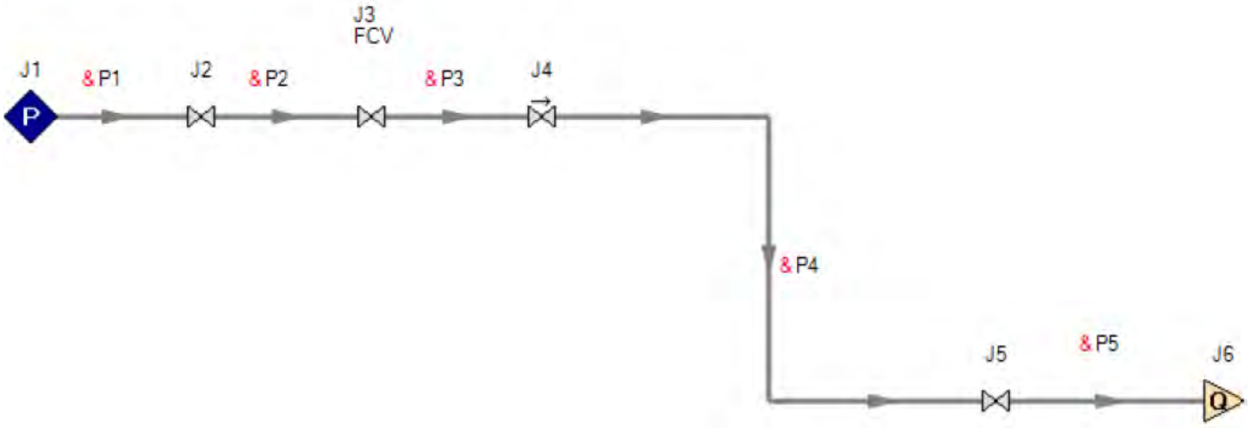

Figure 5-2. 100 MW_{nom} HTEF diagram of steam extraction piping to the reboiler [5].

The reboiler required for heat transfer to the hydrogen production plant is located within the NPP site in a reboiler building adjacent to the turbine building. Refer to Table 5-1, above. The steam extraction operation is like a low-turbine bypass. Since the amount of extracted steam (0.68%) is much lower than the typical capacity of most NPP designs (25% or more), this extraction process will not affect normal plant operation. This design is for extracting 25 MW_t of steam. Out of this 25 MWt power, 20 MWt is used to generate hydrogen while the remaining 5 MW_t is a margin to cover various thermal losses.

5.1.2 500 MW_{nom} High-Temperature Electrolysis Facility Heat Extraction System Design with 105 MW_t Steam Delivery

The HES for a 500 MW_{nom} HTEF is shown in Figure 5-3. The modifications required of the NPP are two steam taps after the HP turbine, a control valve system controlled by the NPP, steam piping leading to a building adjacent to the turbine building, steam connection to two reboilers fed by DI water from the HTEF, and steam piping leading to the HTEF, and DI water piping returning from the HTEF [5]. The reboilers are placed in their own building outside of the turbine building for space consideration, isolation for maintenance, and to protect the turbine building equipment.

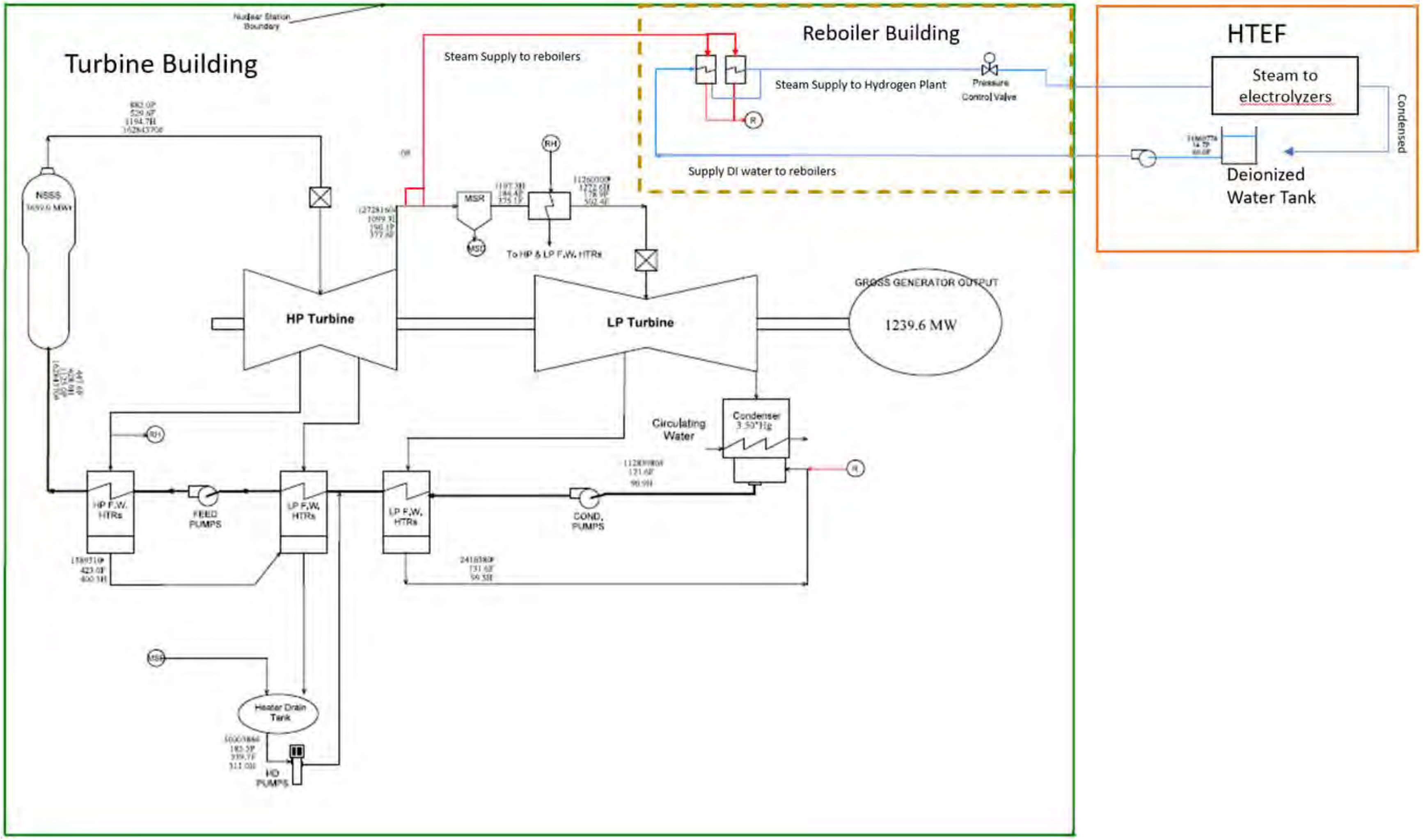

Figure 5-3. Model drawing of 500 MW_{nom} HES.

The PRA requires a specification of the components added as a part of the modification of the NPP that affect the safety of the power plant. The diagram of a steam extraction line downstream from the HP turbine leading to the reboiler is shown in Figure 5-4 [5]. The diameter of the piping header (P5) for the 500 MW_{nom} HTEF is 20 in., 200-ft in length with 14-in. branches, from two taps after the HP turbine and splitting again to two reboilers, a total of 60-ft for each train. This results in a maximum steam velocity of 150-ft/sec. J1 and J21 are taps from the cold reheat discharge from the HP turbine, J2, J7, J22, and J27 are gate valves that are normally open in HES operation. J3 and J23 are flow control valves with a constant pressure drop of 20-psig, assumed to have no flow-stopping capability. J4 and J24 is a stop check 90-degrees globe valve. J8 and J28 are the inlets to the reboilers.

A failure in the steam extraction system up to and including the reboilers will affect the main steam line of the NPP and lead to an increased risk to the NPP. An FT for the line is developed as shown in Figure 7-18.

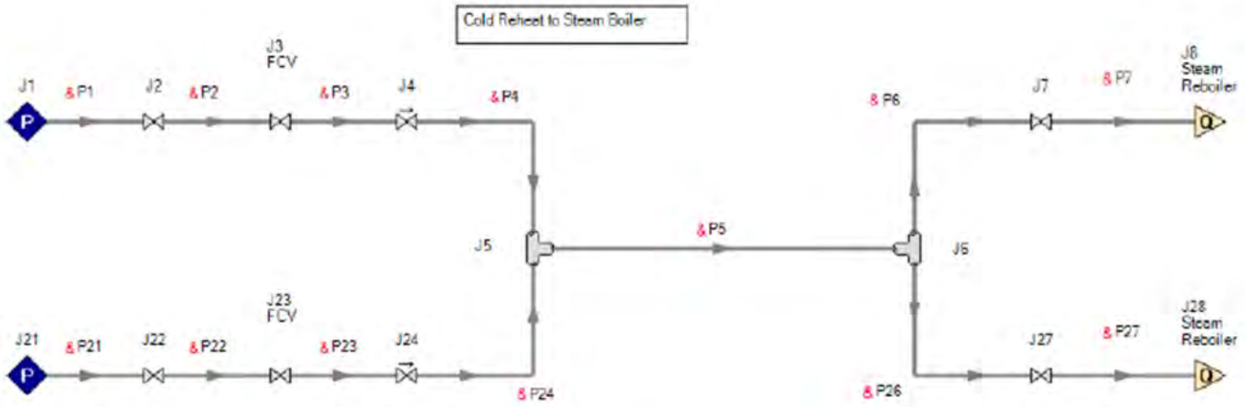

Figure 5-4. 500 MW_{nom} HTEF diagram of steam extraction piping to the reboiler [5].

The reboilers required for heat transfer to the hydrogen production plant are located within the NPP site in a reboiler building adjacent to the turbine building (Figure 5-3). The steam extraction operation is like a low-turbine bypass. Since the amount of extracted steam (2.88%) (Table 5-1), is much lower than the typical capacity of most NPP designs (25% or more), this extraction process will not affect normal plant operation. This design is for extracting of 105 MW_t of steam. Out of this 105 MW_t power, 500 MW_t is used to generate hydrogen while the remaining 5 MW_t is a margin to cover various thermal losses.

5.1.3 1000 MW_{nom} High-Temperature Electrolysis Facility Heat Extraction System Design with 205 MW_t Steam Delivery

It is important to note that unlike the 100 MW_{nom} and 500 MW_{nom} HTEF designs, the 1000 MW_{nom} HTEF HES design was not designed by S&L. It is a design using guidance of the general layout from S&L, but the pipe sizing and lengths were specified through engineering judgment by the INL PRA team. A 15% steam extraction case was modeled in INL/EXT-21-63225, “Evaluation of Different Levels of Electric and Thermal Power Dispatch Using a Full-Scope PWR Simulator” [7] where a 20-in. steam pipe was used. The required 5.62% steam extraction for the 1000 MW_{nom} HTEF is much less than the 15% steam extraction model in Reference [7]. The assumption is made that dividing the cross sectional area of the 20-in.-diameter pipe in half is a conservative estimate to determine the size of steam pipe required. The result of this is a 14-in. pipe. Pipe length before the branches to the three reboilers was assumed to be the100 MW_{nom} HTEF length with an additional 40 ft added because of the increased distance to the main steam line. The pipe sizes and lengths of the reboiler branches were assumed to be 12 in., which is slightly less than the 500 MW_{nom} HTEF because of the higher energy of the main steam.

The HES for a 1000 MW_{nom} HTEF up to is shown in Figure 5-5. The modifications required of the NPP are a steam tap prior to the HP turbine, a control valve system controlled by the NPP, steam piping leading to a building adjacent to the turbine building, steam connection to three reboilers fed by DI water from the HTEF, steam piping leading to the HTEF, and DI water piping returning from the HTEF [5]. The reboiler is placed in its own building outside of the turbine building for space consideration, isolation for maintenance, and to protect the turbine building equipment.

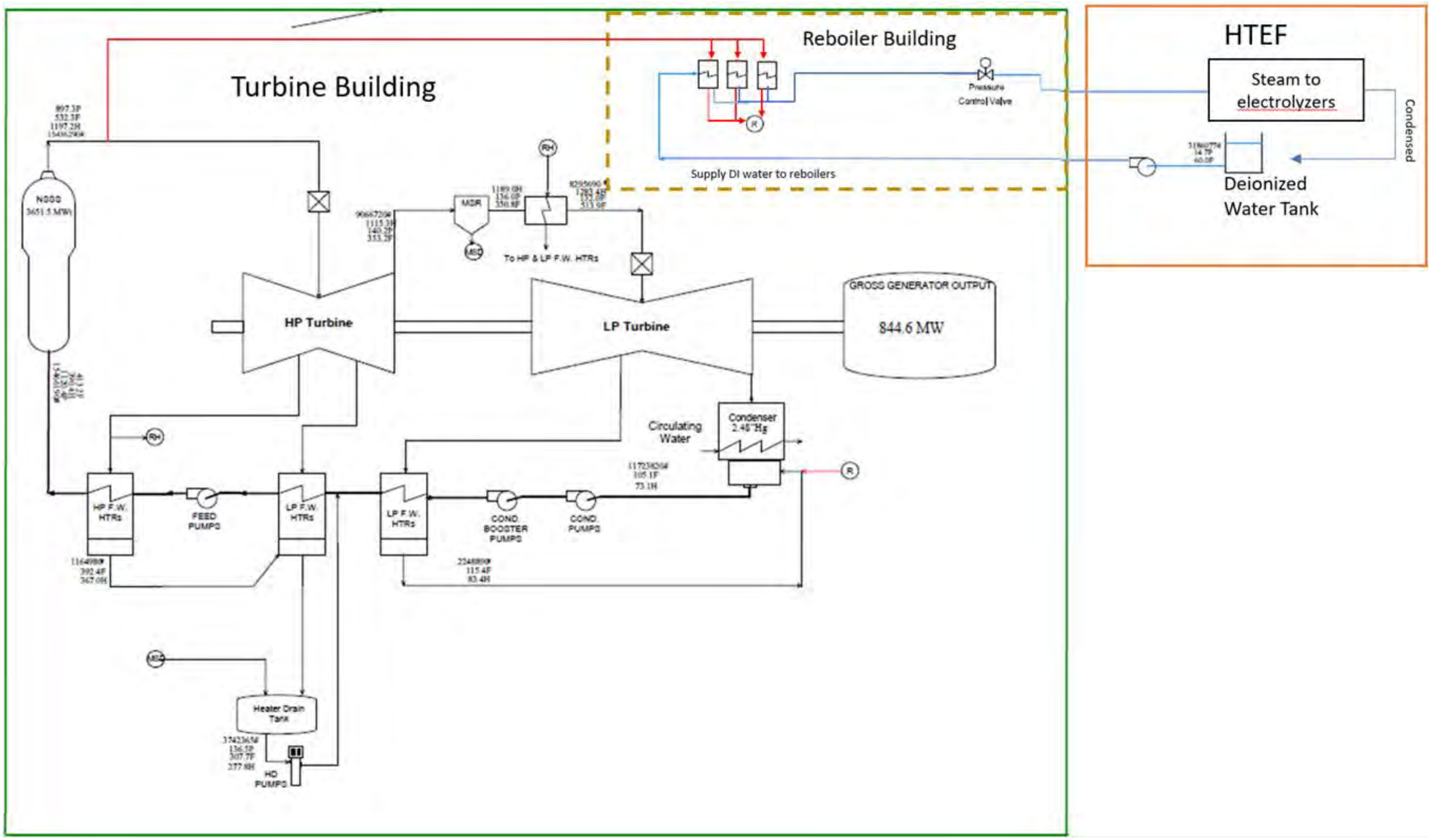

Figure 5-5. Model drawing of 1000 MW_{nom} HES.

The PRA requires a specification of the components added as a part of modifications to the NPP that affects the safety of the plant. Shown in Figure 5-6 is the diagram of a steam extraction line downstream from the main steam tap that leads to the three reboilers. The diameter piping for the 1000 MW_{nom} HTEF is 14 in., 240-ft in length, from the main steam tap to the three reboilers, which are 12-in. pipe branches of a total of 60-ft for each train. This results in a maximum steam velocity of ~150-ft/sec. J1 is a tap from the main steam line prior to the HP turbine, J2, J6, J16, and J26 are gate valves that are normally open in HES operation. J3 is a flow control valve with a constant pressure drop of 20-psig, assumed to have no flow stopping capability. J4 is a stop check 90-degrees globe valve. J7, J17, and J27 are the inlets to the reboilers.

Since a failure in steam extraction lines up to, and including, the reboilers will affect the main steam line of the NPP and lead to an increased risk to the NPP, a FT for the line is developed as shown in Figure 7-19.

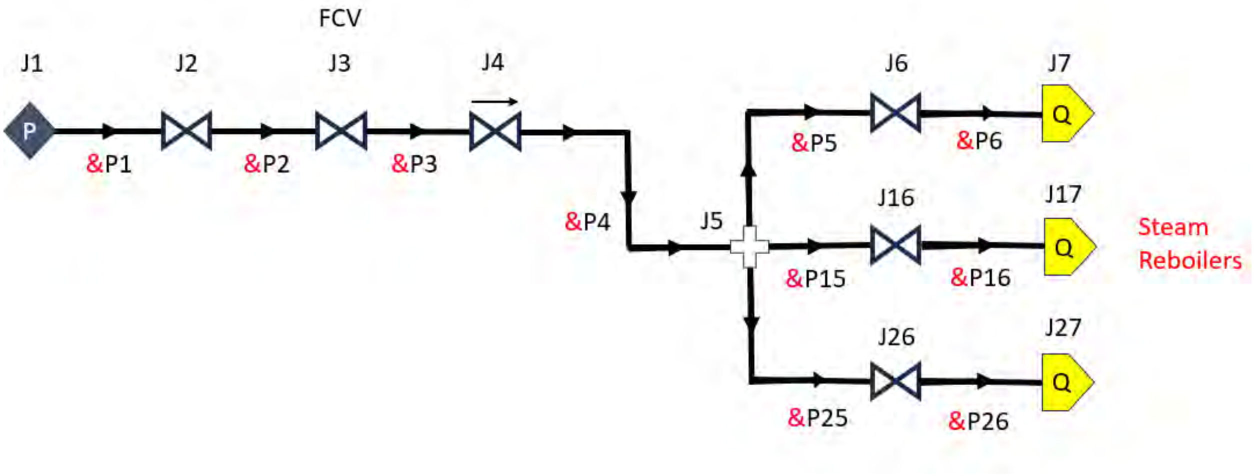

Figure 5-6. 1000 MW_{nom} HTEF diagram of steam extraction piping to the reboiler.

The reboiler required for heat transfer to the hydrogen production plant is located within the NPP site in a reboiler building adjacent to the turbine building (Figure 5-5). The steam extraction operation is from main steam and is like an auxiliary . Since the amount of extracted steam (5.62%) (Table 5-1) is much lower than the typical capacity of most NPP designs (25% or more), this extraction process will not affect normal plant operation. This design is for extracting of 205 MW_t of steam. Out of this 205 MW_t power, 200 MW_t is used to generate hydrogen while the remaining 5 MW_t is a margin to cover various thermal losses.

5.2 Direct Electrical Connection

Refer to Figure 5-7 and Figure 5-8. The electrical connection to the HTEF goes from a tap just outside of the NPP main generator step-up (GSU) transformer to the switchgear at the HTEF. The transmission line distance is determined by the safe standoff distance from the hazards analysis, 345 kV high-voltage 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 NPP switchyard breaker alignment. As stated in Section 4.3.5 of Reference [5], “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 NPP 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 HTEF. The switchgear at the HTEF is interpreted as drawn, 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 NPP boundary and after the safe standoff distance of transmission line are at the HTEF, labeled "H2 Island" in Figure 5-8. Should these protections fail in an overcurrent event due to loads at the medium voltage switchgear or either of the transformers, the resulting overcurrent felt at the generator could cause a transient event at the NPP. This failure model is detailed in Section 7.1.

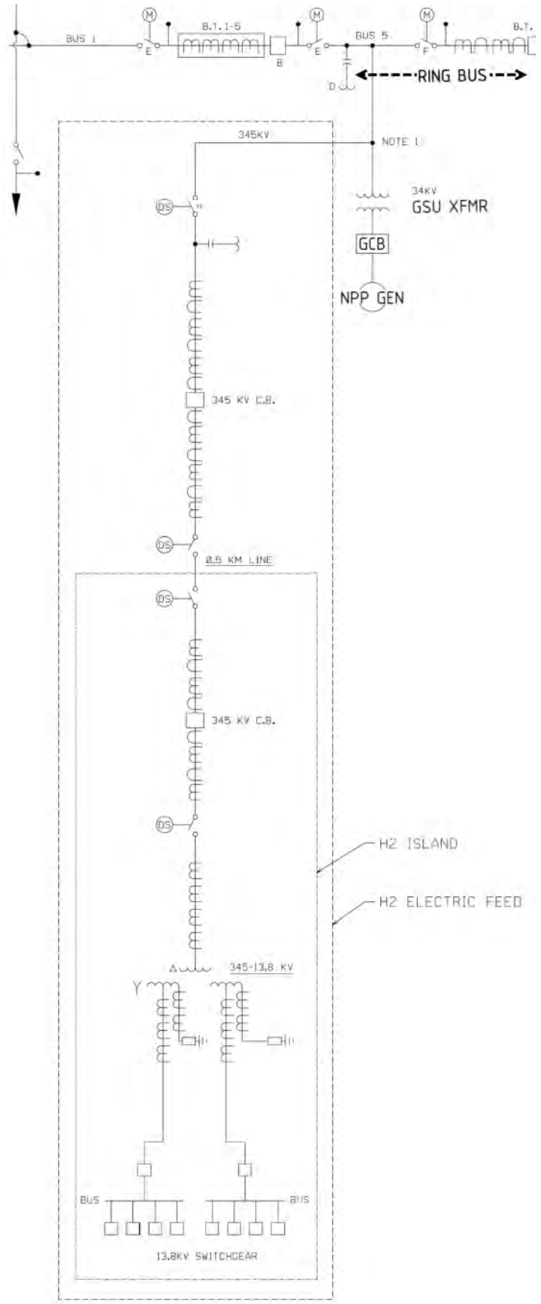

Figure 5-7. Transmission line and portion of ring bus switchyard arrangement at NPP [5].

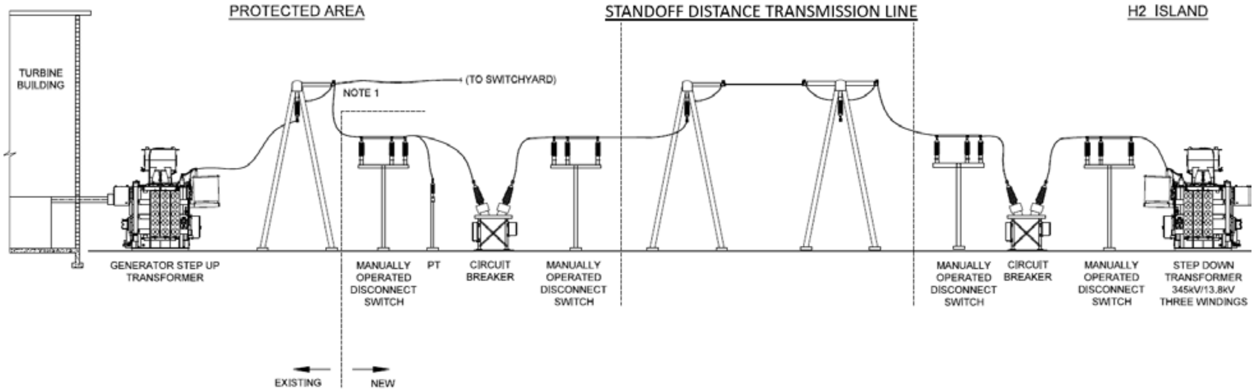

Figure 5-8. Behind the meter physical layout of electrical feeder [5].

6. HAZARDS ANALYSIS

6.1 Nuclear Power Plant with Heat-Extraction System Hazard Analysis

The hazards associated with the addition of the HES to the existing NPP were considered through interviews and failure modes and effects analysis (FMEA) input from subject matter experts (SMEs) from utility engineers, S&L AE engineers, and hydrogen experts at SNL. Proposed design drawings and options of the proposed HES were reviewed and evaluated in a system-level FMEA.

6.1.1 Design Options and Assumptions

The HES and HTEF design options and assumptions considered for the representative NPP, HES, and HTEF are listed in Table 6-1. HES design options reference the P&ID. Other assumptions are made based on physical properties and a generic geographic region.

Hydrogen detonation overpressure is a fraction-of-a-second impulse. Multiple detonations provide follow-on impulses. While it is reasonable to assume that a first impulse may weaken a structure and that a following impulse might damage it, the fragility curves we use in this report are evaluated at the point of zero fragility to the impulse-equivalent psi. For multiple high-pressure jet detonations, it is possible that the first detonation would break another line, providing the opportunity for another high-pressure jet detonation of the same overpressure. An accumulated hydrogen cloud detonation would not cause another hydrogen cloud detonation because the accumulated cloud would be cleared in the first detonation.

Table 6-1. HES and HTEF design options and assumptions.

Component/Parameter	Options	Assumptions
Hydrogen Storage and Transfer Facility	1000 kg of storage is assessed as a sensitivity study	Default assumption is that the HTEF will pipe the production hydrogen to a storage and transfer facility 5 km from the NPP’s critical structures
Electrical Power Linkage from NPP to HTEF	Direct linkage, load following or connection to the grid then to the HTEF	The NPP is connected directly to the HTEF for all sizes of HTEF.

Component/Parameter	Options	Assumptions
HTEF ventilation		All HTEF SOECs are ventilated with explosive proof ventilation. Support structures are designed to not allow any hydrogen accumulation in the event of a leak.
Loss-of-offsite-power (LOOP) frequency		Default LOOP frequency is the same for the generic BWR and PWR model, assuming the same geographical region
Multiple detonations at HTEF		Bounding accident is assumed for the first detonation overpressure. Ensuing detonations will not exceed bounding accident. Structures will not be weakened in the first detonation overpressure.
Temperature of the thermal delivery loop		$\leq 600^{o}$F.
Safety and isolation valves of the HTEF		Isolation and safety valves protect each SOEC and are placed at appropriate points along the low-, medium-, and high-pressure hydrogen lines.
Blast shielding or other engineered barriers at the HTEF other than the combined production header.		Default analysis is performed without shielding.
Shielding of combined high pressure hydrogen production header.		The production header exiting the HTEF is located underground and shielded with concrete. A safe distance sensitivity study is shown for an above ground, unshielded header.
Shielding of 1000 kg hydrogen storage tank		The tank is shielded with an engineered blast barrier because of the possibility of a tank shear and detonation accident.

6.1.2 Nuclear Power Plant Safety-Critical Structures

The reactor building is the primary critical structure at an NPP. 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 refueling water storage tanks (RWST) and condensate storage tanks (CST).

6.1.2.1 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 NPP Structures from Hydrogen Detonation for Gaseous Hydrogen Storage” [8]. The lowest static pressure capacity of nuclear concrete identified is 1.5 psi. This conservative estimate was used for the blast analyses performed in the separation study INL/EXT-05-00137, “Separation Requirements for a Hydrogen Production Plant and High-Temperature Nuclear Reactor” [9] and INL/EXT-19-55884, “Preliminary Probabilistic Risk Assessment of a Light Water Reactor Supplying Process Heat to a Hydrogen Production Plant” [10], and is adopted as the static pressure capability of nuclear concrete walls in this study as well.

NRC Regulation Guide 1.91, Revision 3, “Evaluations of Explosions Postulated to Occur at Nearby Facilities and on Transportation Routes Near NPPs,” [11] uses a 1.0 psi overpressure when calculating safe standoff distances from potential explosion sources.

6.1.2.2 Safety-Critical External Structures Fragility to Overpressure Events

Critical structures outside of the reactor building have been identified when assessing high-wind fragility for PRA. High wind pressure in velocity is easily converted to overpressure in psi. For most BWRs, these include at least one CST. Many times, there is an auxiliary (sometimes called emergency) feedwater tank, service water pump house(s) and intakes, and the electrical switchyard. For PWRs, there is typically an RWST, an auxiliary or emergency feedwater tank, a CST, service water pump house(s) and their associated intakes, and a switchyard. Many wind-pressure and wind-missile fragility studies have been performed for NPPs. The individual plant examination of external events (IPEEE) studies in the 1990s produced a wealth of information on wind fragilities. The Duane Arnold IPEEE [12] was selected as a baseline for these fragilities. An updated high-wind fragility analysis performed by Applied Research Associates [13] determined the mean fragilities components commonly found in the switchyard. These wind pressure fragilities of 6-second gusts are transformed into blast overpressure impulse fragilities in SAND2023-04192, “Risk Analysis of a Hydrogen Generation Facility near a Nuclear Power Plant,” [14]. The formula for the conversion is from SAND2020-7946, “Final Report on Hydrogen Plant Hazards and Risk Analysis Supporting Hydrogen Plant Siting near Nuclear Power Plants” [15].

$$\frac{F_w}{A} = p_d = \frac{1}{2}\rho v^2 \qquad \text{Equation 5-1}$$

Where F_w is the total force in Newtons, A is the effective area in m^2, p_d is pressure in lb_f/in^2, ρ is the air density assumed to be 1.225 kg/m^3 for ambient air conditions, and v is the velocity in m/s [15].

External water tanks are located close to the reactor building to provide condensate storage and coolant for routine and emergency operations. In some cases, there are concrete walls placed around the external tanks for protection, but some NPPs choose not to include external protection other than the tank’s own construction. These tanks are built to extreme standards. According to Reference [12] and other IPEEEs, 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. The probability of failure per instance of overpressure for storage tanks and Category I Structures are listed in Table 6-2. An overpressure event is a fraction-of-a-second impulse, so the correlation between wind speed pressure fragility to overpressure requires proper scaling.

Service water intakes are solid structures, and their failure modes typically involve the buildup of debris on the screens instead of physical damage; however, the pump house is not typically built to withstand tornadic or hurricane winds. In some NPP PRAs, a loss of service water is itself an initiator that challenges the NPP to shut down safely. The probability of failure per instance of wind speed for a typical pump house is listed in Table 6-2.

Loss of switchyard components means a LOOP event that challenges the NPP to shut down safely. Switchyard components are fragile to wind pressure, and therefore also fragile to an overpressure event. The resulting overpressure fragilities for the switchyard are shown in Table 6-2.

Table 6-2. Blast overpressure fragilities of NPP structures, systems, and components (SSCs), both safety and non-safety.

SSC	Effective Pressure (psi)	Equivalent Windspeed (mph)	Total Fragility (Wind and Missiles)
All Category I Structures	0.59	182	0
	0.97	234	4.00E-04
	1.49	290	4.60E-03
	2.16	349	4.00E-02
Storage Tanks (CST, RWST, etc.)	0.59	182	2.10E-03
	0.97	234	2.80E-03
	1.49	290	1.60E-02
	2.16	349	5.40E-02
Circulating Water/Service Water Pump Area in Pump House	0.10	75	8.00E-04
	0.20	105	5.80E-02
	0.28	125	1.50E-01
	0.59	182	5.20E-01
	0.97	234	9.40E-01
	1.49	290	1.0
	2.16	349	1.0
Switchyard, General	0.32	135	3.78E-01
	0.48	165	9.74E-01
	0.71	200	1.0
Transmission Tower	0.10*	75*	0.0*
	0.16*	95*	0.0*
	0.20*	105*	0.8*
	0.32	135	9.18E-01
	0.48	165	1.0
	0.71	200	1.0

SSC	Effective Pressure (psi)	Equivalent Windspeed (mph)	Total Fragility (Wind and Missiles)
Standby Auxiliary Transformer	0.32	135	1.99E-01
	0.48	165	2.68E-01
	0.71	200	3.11E-01
Note: * Updated and lower wind speed and pressure values taken from “Fragility Analysis and Estimation of Collapse Status for Transmission Tower Subjected to Wind and Rain Loads” [21].			

6.1.2.3 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 NPP operations would be affected by damage to the turbine building, administrative building, and maintenance support buildings located throughout the site.

6.1.3 Nuclear Power Plant Hazards Analysis

A group of SMEs were gathered for an FMEA. The team included SMEs with experience in PRA and reliability engineering from INL, PWR operations and BWR operations from INL, and the DOE LWRS sponsored Hydrogen Research Regulatory Review Group (H3RG) consisting of utility, manufacturing and regulatory members, detailed design knowledge of the hydrogen HTEF proposed for this study from INL and S&L, chemical from SNL, and controls experts from S&L and H3RG. Information gathered from the SNL report [15] was used to help determine the external events that could possibly affect the NPP. These included external overpressure events, steam leakage at the HTEF, and electrical power load loss from the HTEF.

The FMEA is required to determine the hazards presented to the NPP. In addition to this FMEA, there was an FMEA performed to explore the hazards presented to the operation of the HTEF and an FMEA performed for public safety and perception. All of these FMEAs identify hazards that are scored with risk profile numbers (RPNs), a number that is used in traditional FMEAs as relative risk-informed information to prioritize what hazards to mitigate first.

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 NPP
- HTEF specification recommendations and assumptions for safety
    - List of HTEFs under consideration
- Thermal and electrical load effects on NPP
    - Thermal and electrical load power profiles supplied by the NPP to the HTEF
- Hot standby mode

- Placement of the HES reboilers
- Unique risks of BWR
- Unique risks of PWR
- Production hydrogen routing options and effects on risk
    - Hydrogen storage risk up to 1000 kg
- A list of heat transfer fluids (HTFs) under consideration and their properties.

Possible external overpressure event effects on the NPP 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. The results of the SNL report on Maximum Credible Accident (MCA) at 500 m distance [15] were known prior to this FMEA.

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

The HES reboilers were considered for placement within the turbine building or in a building separate from 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 (Appendix C) identify.

Unique risks were considered for BWRs and PWRs for each of the hazards identified.

Hydrogen production and storage were discussed as potential hazards. The current model consists of piping the hydrogen to a transfer facility at least 5 km away from the NPP. This facility would consist of truck transfer and other pipeline transfer, including the possibility of mixing with natural gas.

6.1.4 List of Nuclear Power Plant Hazards Identified

The NPP FMEA results are listed in Appendix C. The RPN for each identified hazard was calculated and ranked. RPNs for this exercise are used as risk information. There is no RPN cutoff at which the hazard will not be modeled in the PRA. 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 HTEF 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 HTEF are listed in Table 6-3. Also listed in the table is the event tree that 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 HTEF at a calculated safe distance include a hydrogen detonation at the HTEF causing an overpressure event at the NPP site, an unisolable steam pipe leak in the HES outside of the NPP main steam isolation valves (MSIVs), a reboiler leak in the HES either causing an unisolable steam leak or contaminating the customer HTEF steam loop, and the prompt loss of thermal load to the HES.

Table 6-3. FMEA potential failures from hazards and PRA ET assignment.

Hazards	Potential NPP Process Functions Affected	Potential PRA ET Assignment	FMEA Hazard Status
H2 detonation at HTEF (high-pressure jet detonation, cloud accumulation detonation)	Loss of Offsite Power	Switchyard-centered LOOP (LOOPSW)	Included
	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 (LOSWS) (BWR) No generic PWR tree affected	Included
	Critical Structure Damage (Reactor Containment, CST, or other coolant supply tanks)	HTEF-H2-DETONATION[1]	Included
HES steam pipe rupture outside of NPP MSIVs	Missile damage in turbine building (if HES located in turbine building)	Main (large) Steam Line Break in HES (MSLB-HES) TRANSIENT (MSLB-HES bounding)	Included (screened if HES is not in the turbine building)
	Main (large) steam line rupture, unisolable steam leak	MSLB-HES	Included
HES reboiler leak	Large Leak/Rupture: Main steam line unisolable steam leak	MSLB-HES	Included
	Small Leak: Contamination of the HTEF heating loop (steam or HTF)	Not a design basis event. Economic risk. BWR is a higher risk to contaminate the HTEF heating loop.	Screened for Level-1 PRA. There is an economic and environmental concern
Prompt steam diversion loss, feedback	Maximum of 5.26% thermal diversion for 1000 MW_{nom} HTEF	None. NPP can handle 30% prompt load loss. Screened out.	Screened
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

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[1] Potential new ET if evaluated overpressure damages critical structures.

Hazards	Potential NPP Process Functions Affected	Potential PRA ET Assignment	FMEA Hazard Status
Use of HTFs instead of steam	Leak potential in heat exchanger or reboiler Fire potential in reboiler room	TRANSIENT	Not included in modeled designs for this report. See Reference [1], Section 4.1.2 for a representative HES design Properties of HTFs are listed in this report
Stacked SOEC module topples due to a wind or seismic event	Loss of Offsite Power	Switchyard-centered LOOP (LOOPSW)	Screened out by meeting facility design standards
	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 (LOSWS) (BWR) No generic PWR tree affected	Screened out by meeting facility design standards
	Critical Structure Damage (Reactor Containment, CST, or other coolant supply tanks)	HTEF-H2-DETONATION[2]	Screened out by meeting facility design standards

6.1.4.1 Hydrogen Leakage at the HTEF

The leak frequency of the facility was calculated from the bottom-up component leak frequencies. A Bayesian statistical analysis was used to combine leak events from non-hydrogen sources that are representative of hydrogen components with limited data for leak events from hydrogen-specific components. The overall leak rate is given for several leak sizes, starting from 0.01% to 100% (guillotine break) of the pipe size. SNL analyzed the leak frequencies using conceptual designs and performed a sensitivity analysis of ±10% number of components to account for design uncertainties [15]. The overall leak rates for the system of 100 MW, 500 MW, and 1000 MW are listed in Table 6-4 to Table 6-6.

The leak frequencies of the 500 MW and 1000 MW HTEF design are relatively high because there are more SOEC units and piping than the 100 MW design where leaks can happen. While the 100 MW HTEF has 60 SOEC units, the 500 MW and 1000 MW have 300 and 600 SOEC units, respectively. The leak frequencies from the SOEC units alone are listed in Table 6-7. Because only the SOEC units are installed within closed enclosures, these SOEC leak frequencies will be used to calculate cloud detonation risks.

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[2] Potential new ET if evaluated overpressure damages critical structures.

Table 6-4. 100 MW HTEF System Leak Frequency (/y).

Leak Size	100 MWt HTEF Module System Leak Frequency			
	Mean	5th	Median	95th
0.0001	1.80E+01	1.19E+01	1.74E+01	2.86E+01
0.001	3.50E+00	1.72E+00	3.18E+00	6.96E+00
0.01	1.09E+00	3.23E-01	9.26E-01	2.90E+00
0.1	1.57E-01	8.60E-02	1.63E-01	2.84E-01
1	8.57E-02	3.11E-02	7.95E-02	2.01E-01

Table 6-5. 500 MW HTEF System Leak Frequency (/y).

Leak Size	500 MWt HTEF Module System Leak Frequency			
	Mean	5th	Median	95th
0.0001	8.98E+01	5.95E+01	8.68E+01	1.30E+02
0.001	1.75E+01	8.63E+00	1.59E+01	3.17E+01
0.01	5.43E+00	1.62E+00	4.23E+00	1.32E+01
0.1	7.94E-01	4.35E-01	7.48E-01	1.31E+00
1	4.34E-01	1.57E-01	3.66E-01	9.27E-01

Table 6-6. 1000 MW HTEF System Leak Frequency (/y).

Leak Size	1000 MWt HTEF Module System Leak Frequency			
	Mean	5th	Median	95th
0.0001	1.80E+02	1.19E+02	1.74E+02	2.61E+02
0.001	3.50E+01	1.73E+01	3.19E+01	6.35E+01
0.01	1.09E+01	3.24E+00	8.45E+00	2.65E+01
0.1	1.59E+00	8.71E-01	1.50E+00	2.62E+00
1	8.69E-01	3.15E-01	7.32E-01	1.85E+00

Table 6-7. Leak frequency of SOEC units only (/y).

Number of SOECs	Leak Frequency		
	Mean	5th	95th
1	6.91E-04	5.00E-05	2.42E-03
60 (100 MW)	4.15E-02	3.00E-03	1.45E-01
300 (500 MW)	2.07E-01	1.50E-02	7.27E-01
600 (1000 MW)	4.15E-01	3.00E-02	1.45E+00

6.1.4.2 Hydrogen Detonation at the HTEF

Another possible hazard identified is hydrogen leakage and explosion. The severity of hydrogen explosion and its annual frequency for all HTEFs considered in this report was calculated in a reference report [14]. The most susceptible SSC in the NPP is the switchyard transmission tower (Table 6-2). Using the assumptions in this report (Table 6-1) and the safe siting distances calculated, the only DBA affected by a detonation at the HTEF is the switchyard centered LOOP.

The bounding deterministic analyses performed for resultant overpressure versus distance did not credit attenuation of the shock wave made by engineered blast barriers, buildings, wooded areas, or other topography. It is easy, but expensive, to just require that proven adequate barriers be built as part of the HTEF. This report provides the safe siting distance at which engineered barrier requirements are at a minimum. The safe distancing criteria presented in Section 6.1.5 recommends engineered barriers for the 500 and 1000 MW_{nom} HTEF production header to maintain the same safe standoff distance of the 100 MW_{nom} HTEF. Safe distances for the unprotected common production headers (CPH) are also provided but one of the most important assumptions of this report (Table 6-1) is that these CPHs are protected.

The overpressures felt at the NPP from a high-pressure jet leak detonation or a hydrogen cloud accumulation detonation shown in Table 6-8 were determined based on 15 leakage scenarios [14]. The bounding case presented in Reference [14] used the largest leak size and therefore these frequencies were used in the PRA IE development. Calculations were made for the next-largest leak size, denoted 0.1, and the most fragile components of the NPP were not affected by the overpressures created from either the high-pressure jet or hydrogen cloud detonation.

Table 6-8. Hydrogen high-pressure jet detonation overpressure safe distance

HTEF Pressure Section	H_2 Pressure (psi)	Safe Distance (m)
All HTEF low pressure section	< 5	21
All HTEFs medium pressure section	300	102
All HTEFs high pressure section	1500	187
100 MWnom HTEF combined production header	1500 with higher volume	187
500 MWnom HTEF combined production header	1500 with higher volume	530
1000 MWnom HTEF combined production header	1500 with higher volume	681

6.1.4.2.1 High-Pressure Jet Detonation:

The high-pressure jet detonation frequency is not determinant on the human action to isolate the leak. The hydrogen is immediately available for detonation as calculated in the SNL reference [14]. The total fragility of switchyard components resulting from wind pressure and tornado-generated missiles is listed in Table 6-2. This fragility data is used to determine the failure probability of these components when a hydrogen detonation event occurs. Determination of a safe distance for all but the CPH leaving the HTEF in Section 6.1.5 defined the minimum safe distance between the high pressure section of the HTEF and the switchyard transmission tower is 187 meters. This is the distance at which the transmission tower fragility is zero.

The fragility data points for an unprotected CPH are shown in Figure 6-1, along with fragility data from most damaging high-pressure jet detonations in 100, 500, and 1000 MW_{nom} HTEF designs located 187 meters away. Fragility estimates between the known data points are interpolated linearly. The most fragile component in the switchyard is the transmission tower. The probability for damaging a transmission tower goes to zero at approximately 0.16 psi Table 6-2 [21]. For reference, windows will break at an incident overpressure between 0.15 and 0.22 psi (Federal Emergency Management Agency, citing Kinney and Graham, “Explosive Shocks in Air” [23]), so the damage to the transmission tower is not expected to be catastrophic (e.g. a toppled tower) at 0.20 psi, but it will disrupt power transmission.

The figure shows that if the CPH is not protected the 500 and 1000_{nom} MW HTEFs will certainly damage the transmission tower if an MCA high-pressure jet detonation occurs. The MCA scenario from these designs originate from hydrogen leakage at the CPH section which is used to transport hydrogen to a storage facility. If this CPH is constructed above ground, it will create a jet-detonation overpressure of 0.84 psi for 500 MW_{nom} and 1.33 psi for 1000 MW_{nom} HTEFs at 187 meters away. The switchyard fragility reaches maximum at these overpressure values. Even the exterior tanks and Category I structures show some fragility at 1.33 psi. For that reason, it is necessary to shield this CPH section with natural and/or engineered barriers, for example by using our assumed construction underground and reinforcing it with blast barriers, to reduce the overpressure to less than 0.16 psi.

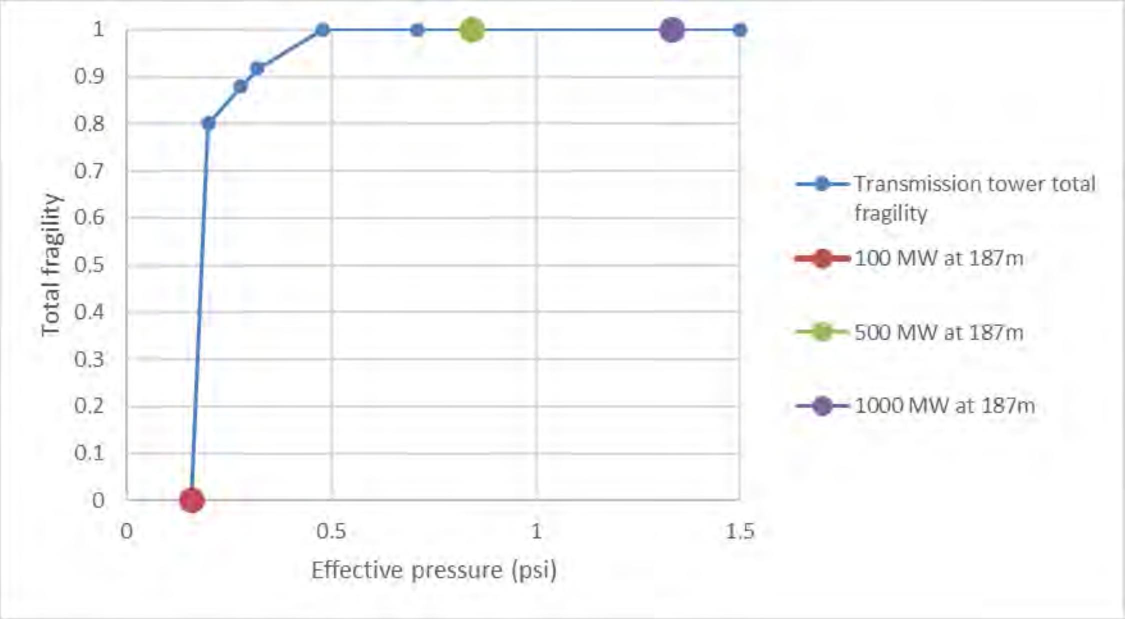

Figure 6-1. Switchyard transmission tower fragility as a function of pressure.

The representative FT developed for this event is the branch beginning with the AND logic gate IE_LOOPSC-HES-HES33 in Figure 7-20Figure 7-20. Total frequency of LOOP with Hydrogen Production Facility (IE-LOOPSC-HES).. Note that at the deterministic safe distances and model assumptions the event “Switchyard failure due to jet H2 explosion”, IE-LOOPSC-SC-JET-F, is a probability of zero. The model is provided for reference.

6.1.4.2.2 Hydrogen Cloud Detonation:

The hydrogen cloud detonation frequency is determinant on the ability of hydrogen to accumulate within the HTEF SOEC containment structure. The enclosure considered in this study is a container measured 8 × 52 feet. This is determined by the failure of the ventilation system to vent the leak to atmosphere and the failure of human action to isolate the leak within the specified time noted in Reference [14]. For the MCA, this time is 120 minutes. The failure of all modes of an industrial building ventilation system was noted to be 2.4E-05/h in INEEL-EXT-99-001318, “Ventilation Systems Operating Review for Fusion Systems” [40]. This is a conservative estimate of ventilation failure for the SOEC containment structures where ventilation of easily dispersed hydrogen is a primary design parameter. The human action probability of failure was determined using the standardized plant analysis risk human reliability analysis (SPAR-H) methodology within SAPHIRE to be conservatively 1.0E-2, given nominal time to perform the action and all other performance shaping factors (PSFs) listed as nominal. The probability of detonation, given a leak is 0.35 [22]. These probabilistic events, along with the yearly frequency of 6.91E-4/y for the full leak in a SOEC containment structure (Table 6-7) creating the MCA times the number of SOECs in the representative 100, 500, and 1000 MW_{nom} HTEFs (Table 6-7), were modeled in an FT to determine the frequency per year of the cloud detonation MCA event for each HTEF. This FT is the branch beginning with the AND logic gate IE_LOOPSC-HES-HES34 in Figure 7-20Figure 7-20. Total frequency of LOOP with Hydrogen Production Facility (IE-LOOPSC-HES).. The resulting frequency of IE_LOOPSC-HES-MCA is 3.49E-09/y. This is seven orders of magnitude below the loss-of-offsite-power switchyard-centered (LOOPSC) IE frequency of 1.34E-02/y (basic event IE-LOOP-SC) for both the BWR and PWR models described.

An FT is constructed for each HES design, as shown in Figure 7-20, to model this additional risk. The switchyard component may fail when a hydrogen leak occurs with frequencies listed in Table 6-7, plant operator fails to isolate the leakage within 2 hours, the ventilation system fails to disperse the hydrogen to the atmosphere, and a spark occurs igniting the accumulated hydrogen cloud. This is the MCA scenario highlighted in Figure 6-2, which is assumed to be the bounding accident to damage the switchyard components. The hydrogen ignition probability is a function of hydrogen leakage rate [22]; however, in this FT, a conservative probability value of 0.35 is selected for the event. This scenario ignites a total of between 0.42 to 0.68 kg of hydrogen and creates an overpressure of 0.78 to 0.97 psi to the NPP structures located 187 m from the HTEF high pressure section. The amount of accumulated hydrogen cloud is taken from a reference study which lists hydrogen concentration ranging from 15% to 24% volume in a shipping container enclosure [24]. This overpressure will fail the switchyard components with a statistical probability of 1 and create a LOOP event. As with the steam line break hazard, the top event of this FT is set as the total initiator frequency for the new LOOP ET as shown in Figure 7-14.

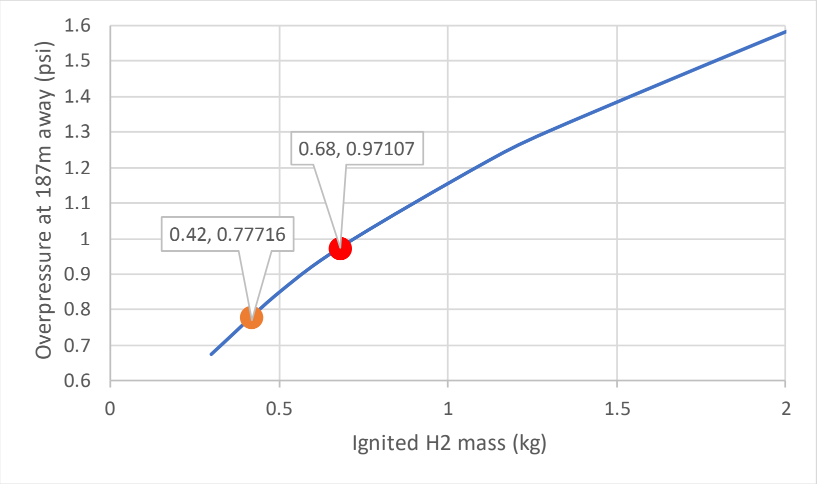

Figure 6-2. Overpressure at a distance of 187 meters due to hydrogen cloud detonation.

It is conservatively assumed that the hydrogen cloud detonation scenario always leads to the MCA scenario. With this assumption, the probability for an MCA scenario is 1 whenever there is an unmitigated hydrogen leakage. This conservative assumption is because of the absence of data available on the time distribution of uncertainty sources affecting the hydrogen leakage time (i.e., operator's timing to isolate the leakage, timing of spark occurrences, and building ventilation). These uncertainties may lower the probability for an MCA event. For example, if the leakage time is assumed to occur uniformly between 5 and 120 minutes, the total fragility may be calculated by uniformly sampling the quantity of released hydrogen in Figure 7-20 up to the MCA scenario and performing a look-up conversion of the detonation's overpressure to the switchyard fragility using Figure 6-1.

This event can be screened out probabilistically by the results of the conservative values FT analysis. The frequency of the occurrence of this event for the bounding 1000 MW_{nom} HTEF is 3.5E-08/y. This is a value six orders of magnitude below the switchyard centered LOOP. It is also a value regularly screened out from external hazards assessments.

This event cannot be screened deterministically unless a safe siting distance is determined for the closest SOEC module container to the switchyard transmission tower. This distance would be approximately equivalent to the 681 m distance required for the 1000 MW_{nom} combined production header. Engineered blast barriers could eliminate this risk.

6.1.4.3 Heat Extraction System Unisolable Steam Pipe Rupture

A large steam line break is the most common hazard introduced by adding the HES to the NPP. There is one isolation valve immediately after the steam tap for each of HES designs listed in Section 5.1. The success of this valve is the first line of defense of a steam line rupture within the HES after the NPP's MSIVs have failed to isolate. Isolation and control valve ruptures are also a possibility that needed modeling. After the isolation valves, all the other active components listed in Section 5.1 are evaluated in the HES FTs (Sections 7.2 and 7.3). The FT result was added to the IE for a large steam line break, as described in Section 7.2.1 for a PWR and Section 7.3.1 for a BWR.

Seismic considerations were also added to the IE for a large steam 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 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 6-9.

Table 6-9. 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 [REF- NUREG/CR-4334]. The fragility constants and which valves they were applied to are documented in Table 6-10.

Table 6-10. Seismic fragility constants for valves evaluated in main steam line break.

<table>
<tr><th colspan="2" rowspan="2">Valve Type</th><th colspan="3">Seismic Lognormal Fragility Constants</th></tr>
<tr><th>Am (g)</th><th>βr</th><th>βu</th></tr>
<tr><td colspan="2">Gate valve as a motor operated valve (MOV)</td><td>3.10</td><td>0.24</td><td>0.37</td></tr>
<tr><td colspan="2">Check valve (CKV)</td><td>1.40</td><td>0.34</td><td>0.30</td></tr>
<tr><td>Flow control valve (FCV)[3]</td><td>3.10</td><td>0.24</td><td colspan="2">0.37</td></tr>
</table>

6.1.4.4 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 NPP operation and a reboiler rupture. The reboiler faults are considered equivalent to heat

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[3] Used MOV data for the FCV

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 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 Reboiler: The heat-transfer loop to the HTEF will always be operating at a lower pressure than the NPP steam loop through the HES. This prevents the contamination of the NPP steam loop. Small leaks in the reboiler may contaminate the heat-transfer loop to the HTEF. This can cause a cleanup problem if there is enough activity transferred to the heat-transfer loop. For most NPPs, this will not be a problem. BWR steam loops are more likely than PWR steam loops to have radioisotopes of any measure, but their steam loops are typically very clean as well. This is a unique potential hazard to the LWR NPPs considering this modification. There are prevention, detection, and mitigation measures that obviously would need to be in place to monitor for and react to any small leaks. This hazard can cause economic issues for the cleanup, including reactor shutdown, and cause environmental concerns in the public. This study is concerned with reactor safety and did not consider the architecture of a representative system.

Rupture of an HES Reboiler: Depending on the size of the supported HTEF, 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 for PWRs (Section 7.2.1) and BWRs (Section 7.3.1).

6.1.4.5 Prompt Steam Diversion Loss Causes Feedback

The addition of the HES to the NPP provides a new steam loop that must be evaluated for safety. The design considered for this study assumes that the amount of steam diversion is limited to 5% of the total steam production. This screens out one of the postulated hazards (Table 6-3), that the prompt load drop was felt by the NPP and pushed to the turbines, even with the successful closing of the HES isolation valves. The FMEA team determined that LWR NPPs can withstand up to a 25% load drop without having to trip.

6.1.4.6 Use of Heat Transfer Fluids and Ignition Potential

The use of steam as the heat-transfer medium screens this hazard out from consideration. HTFs have desirable qualities of consistent thermal storage for longer distances and periods of time than steam. While steam is the medium of choice of most NPP operators interviewed, there is a possibility that HTFs will be considered. Four representative HTFs with a range of operating temperatures and states are listed in : Therminol 66, Dowtherm A, Dowtherm G, and Therminol VP-1. HTF ignition would result from a leak with an ignition source at a temperature above the flash point or over-heating the HTF to the auto-ignition temperature in the presence of oxygen. HTF leakage probability was not determined for this study.

A leak and fire within the reboiler building could damage the equipment and cause the NPP to isolate the HES. If the fire is severe enough, there is a possibility of damaging the ability to isolate the HES without closing the NPP’s MSIVs.

Table 6-11. Heat-transfer fluid properties.

Heat-Transfer Fluid	Max Operating Temperature (°F)	Flash Point (°F)	Auto-ignition (°F)
Dowtherm A	494 (liquid) 495–750 (vapor)	236	1110
Dowtherm G	675 (liquid)	280	810

Heat-Transfer Fluid	Max Operating Temperature (°F)	Flash Point (°F)	Auto-ignition (°F)
Therminol 66	650 (liquid)	338	705
Therminol VP-1	256 (liquid) 257–750 (vapor)	230	1114

6.1.5 High Temperature Electrolysis Facility Siting Analysis

The placement of the HTEF is determined first and foremost by the safety of the NPP and the public. Other considerations are made due to the geographical properties of the existing NPP site, the proximity to the reboiler building to make the steam supply line as efficient as possible, and the accessibility of the HTEF for transport of the hydrogen product. The following sections provide analyses useful to visualize the size of HTEFs considered in this report, the standoff distances required for these sizes, and where in the HTEF these overpressure hazards are located.

To put these hazards into context, multiple locations across the United States were examined. First, existing NPPs were selected, and a site analysis was performed on them to understand what features should be considered. Features that were determined included population centers, transmission line paths, public service structures such as water towers and gasoline stations, and natural geographic features such as hills, lakes and wetlands. Next, a set of generic sites that contained these features were selected and a site analysis was performed on it. The selected set included three sites: (1) riverside with wetlands, (2) remote desert site, and (3) lakeside with nearby town.

In previous analyses, the Bauwens-Dorofeev (Bauwens) hydrogen jet leak detonation overpressure methodology [14] found that the high pressure sections required a minimum safe distance of 500 m for a 100 MW_{nom} HTEF [1] to experience no more than 016 psi. The more developed specifications of the HTEFs in this report resulted in both the Bauwens and TNT equivalence methods yielding much lower minimum safe distances (Table 6-8).

For the TNT equivalence method as prescribed by NRC RG 1.91 [11] all safety-related SSCs would have to experience a peak positive incident overpressure of no more than 1.0 psi [11]. The safe distances for no more than 1 psi are correspondingly lower as are shown in the following sections.

6.1.5.1 100 MW_{nom} High Temperature Electrolysis Facility Siting Analysis

The site analysis for 100_{nom} MW HTEF considered hazards due to two generic layouts with minimum safe distance radiuses calculated (Table 6-8). The two layouts designed by S&L are shown in Figure 4-1 and Figure 6-3. One layout is rectangular and the other square to help fit in local sites. Analysis was done with respect to three different levels of pressure shown by the low (< 5 PSIG in red, Scenario 1-3 from [14], intermediate (200–300 PSIG in blue, Scenario 4-5 from [14], and high (approximately 1500 PSIG in green, Scenario 6 from [14] pressure sections.

For the Bauwens method, we consider the minimum safe distance to be where 0.16 psi is experienced for the most fragile SSC (switchyard transmission tower). The zero fragility threshold for the transmission tower is at 0.16 psi (Table 6-2). Analyses from [14] show that the low-, intermediate-, and high-pressure sections have a minimum safe distance radius of 21, 102, and 187 m respectively.

For the TNT equivalence method as prescribed by NRC RG 1.91 [11] all safety-related SSCs would have to experience a peak positive incident overpressure of no more than 1.0 psi. Analysis from [14] shows that the low-, intermediate-, and high-pressure sections have a minimum safe distance radius of 10, 49, and 81 m respectively.

A third analysis was considered to compare the Bauwens method and the TNT equivalence method directly at 0.16 psi overpressure, but ultimately was not done because of domain of the overpressure chart that is widely accepted and used in HyRAM+ [14][22] does not extend below 0.49 psi [16]. Extrapolation of the data would introduce an unknown amount of uncertainty and therefore not produce credible results.

Another standoff considered is the National Fire Protection Association (NFPA) standoff for industrial hydrogen of 33 m from the perimeter of the HTEF [17]. Annotated versions of the layouts and the safe standoff distances (Table 6-8) are shown in Figure 6-4 and Figure 6-5.

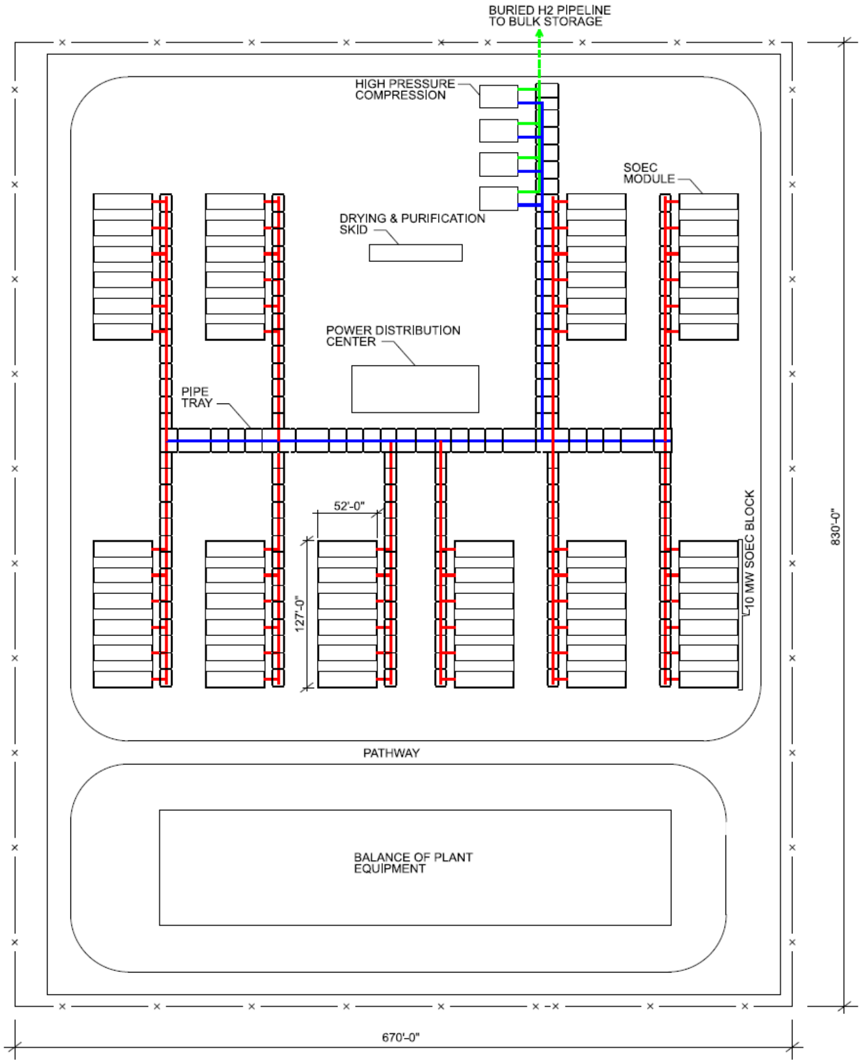


Figure 6-3. 100 MW_{nom} high-temperature electrolysis plant layout 2 with 670 ft × 830 ft footprint.

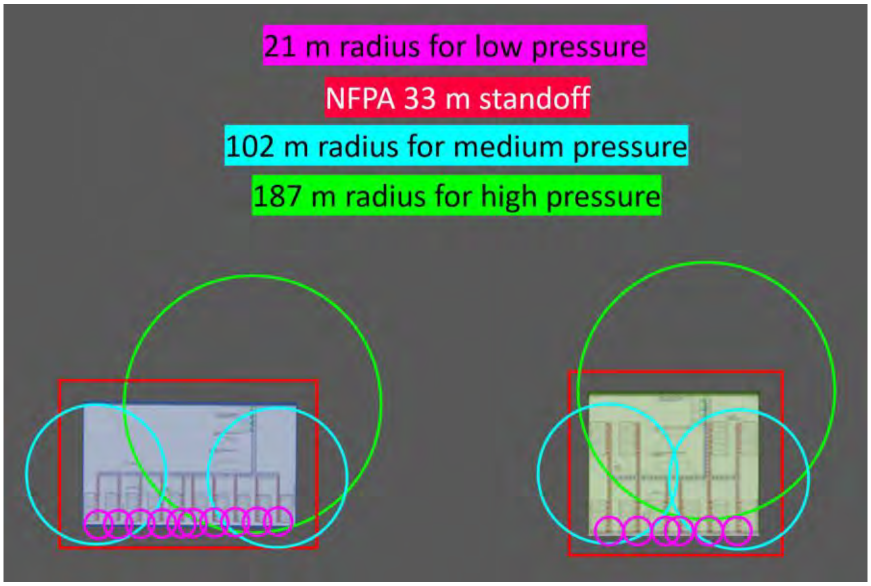


Figure 6-4. Plant layouts for a 100 MW_{nom} HTEF with imposed minimum safe distance radiuses and NFPA standoff distances using the Bauwens method.

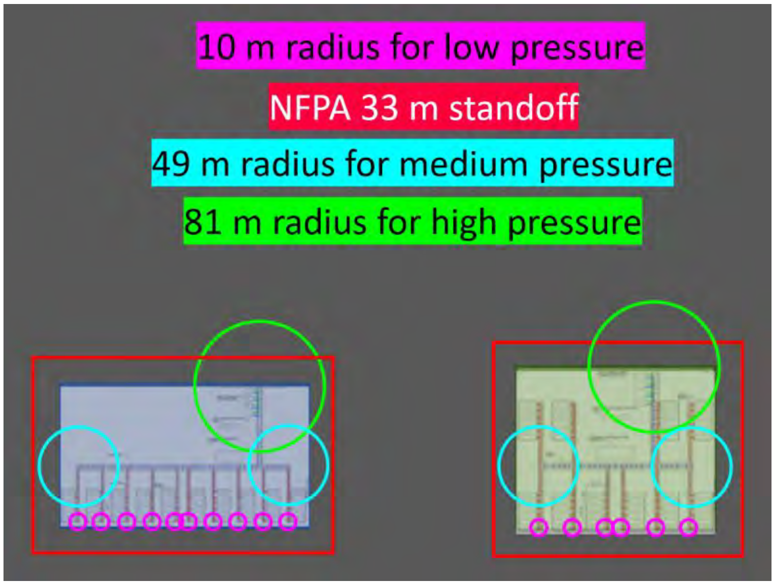


Figure 6-5. Plant layouts for a 100 MW_{nom} HTEF with imposed minimum safety distance radiuses and NFPA standoff distances using the TNT equivalence method for satisfying NRC RG-1.91 [11].

Each site includes multiple options of generic HTEF layouts with the imposed radiuses and standoffs as shown in, and a generic NPP layout including spent fuel cask storage, security and safety boundaries, power plant switchyard, and the connected transmission lines. Along with the transmission lines and switchyard, other hazards unique to each site are annotated. The first site, riverside with wetlands (Figure 6-6 and Figure 6-7) highlights the various buildings and other infrastructures of interest. The buildings in the HTEF and the NPP are consistent through all four sites.

For this first site the HTEF can be located directly adjacent to the NPP and the transmission line without risk of damaging either infrastructure. Other infrastructure shown that is out of range of overpressure effect is the interstate highway marked in light yellow.

Figure 6-6. Bauwens Analysis for a 100 MW_{nom} HTEF of Site 1, "Riverside with wetlands."

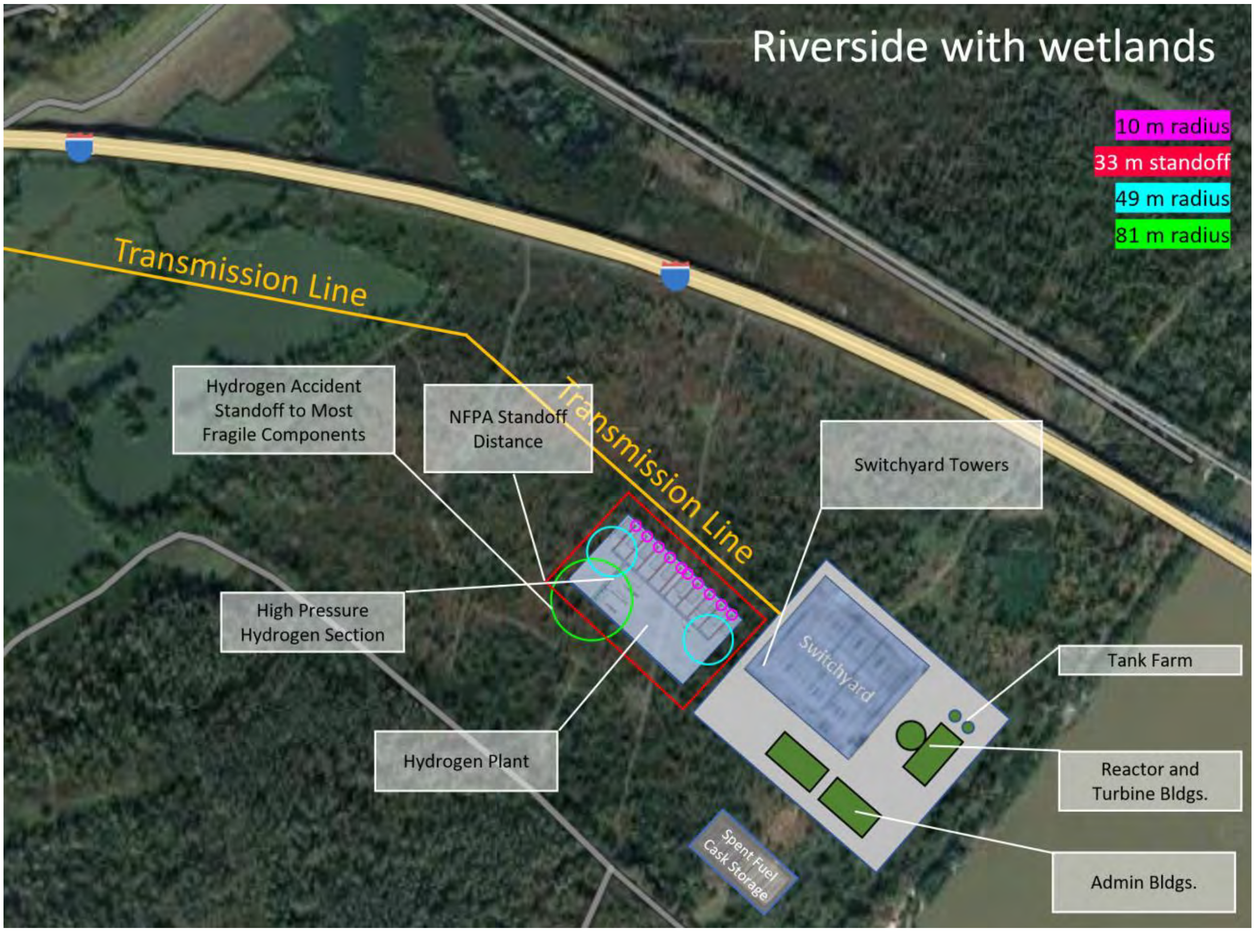


Figure 6-7. NRC RG-1.91 [11] Analysis for a 100 MW_{nom} HTEF of Site 1, "Riverside with wetlands."

Site 2, as shown in Figure 6-8 and Figure 6-9, is a hypothetical remote desert site chosen to exhibit a location requiring consideration of a significant ultimate heat sink water pipeline and pumphouse, but not consideration of any population centers. This location also shows safety and security boundaries more concretely such as the property boundary, personnel fences, and the protected area. In such a remote site, there is more flexibility in siting the hydrogen facility since there are no nearby populations. The figure shows that the HTEF plant can be located inside the protected area safely.

Figure 6-8. Bauwens Analysis for a 100 MW_{nom} HTEF of Site 2, “Desert.”

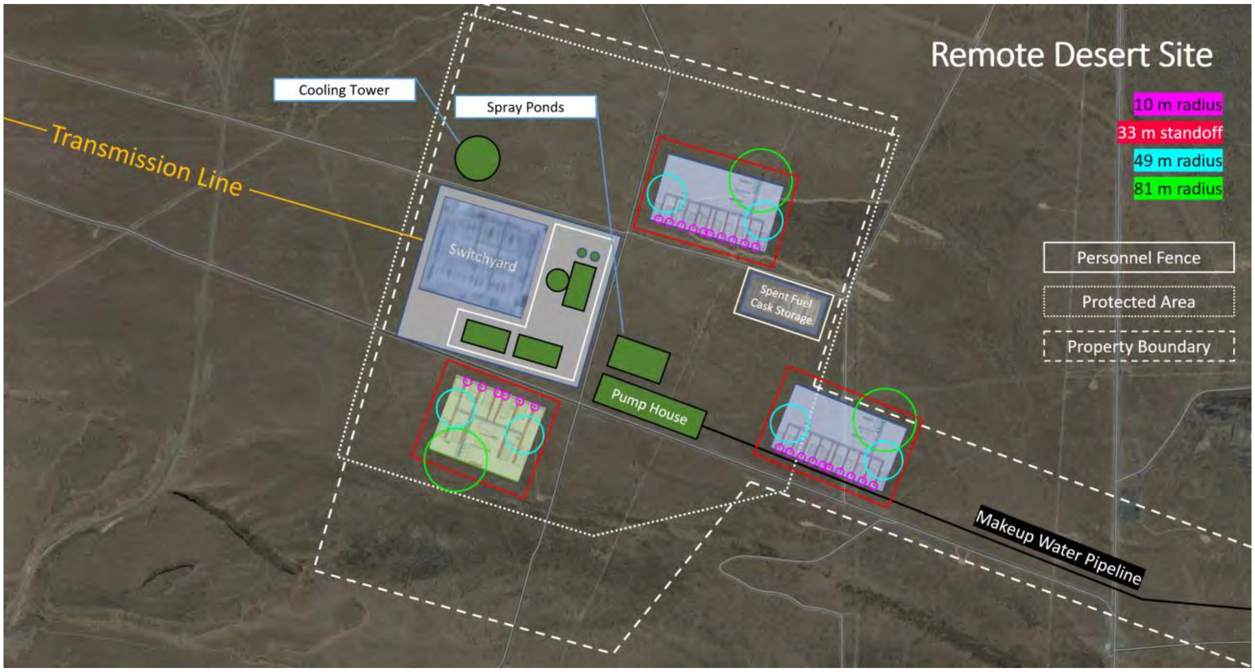


Figure 6-9. NRC RG-1.91 [11] Analysis for a 100 MW_{nom} HTEF of Site 2, “Desert.”

The third site considered is located by a lake near a populated town as shown in Figure 6-10 and Figure 6-11. There is less flexibility here to locate the HTEF due to nearby residential areas and public buildings such as the school and housing. However, it is still possible to construct the HTEF safely given that there is a sufficient undeveloped area owned by the licensee. The two sites shown are the closest viable sites to the turbine building. Note that engineered blast barriers would need to be in place for the eastern site to protect plant support building windows.

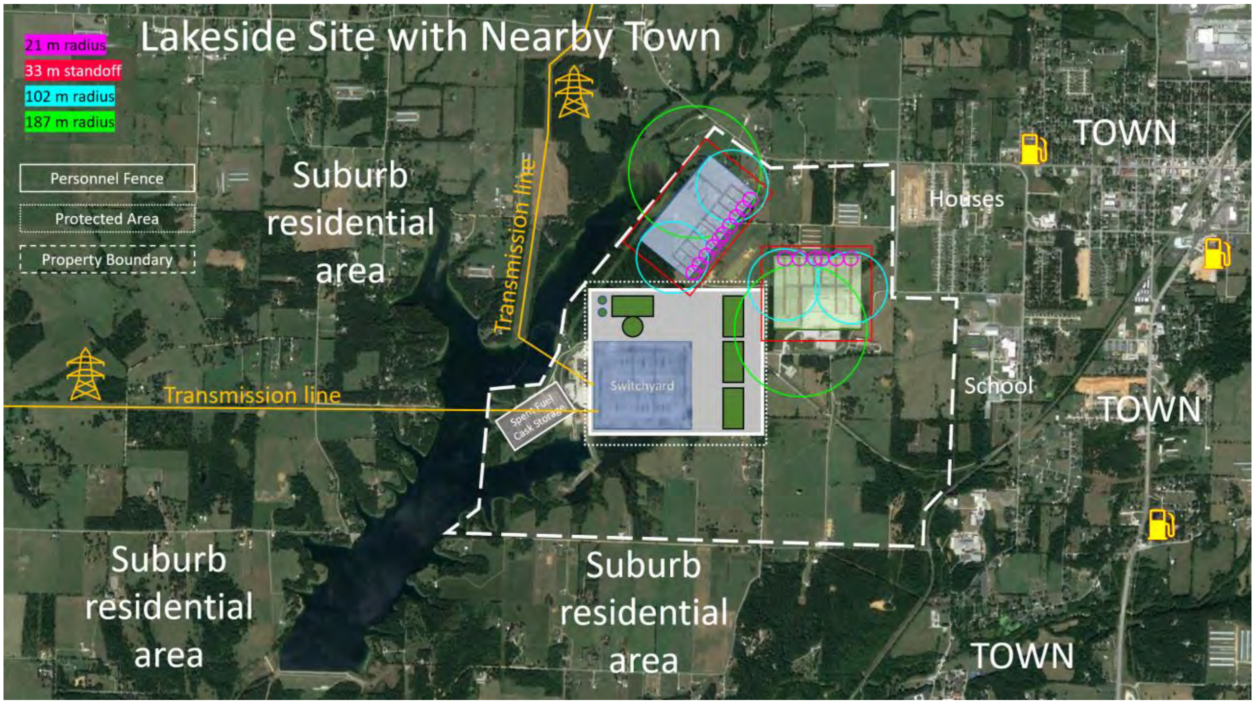


Figure 6-10. Bauwens Analysis for a 100 MW_{nom} HTEF of Site 32, "Town."

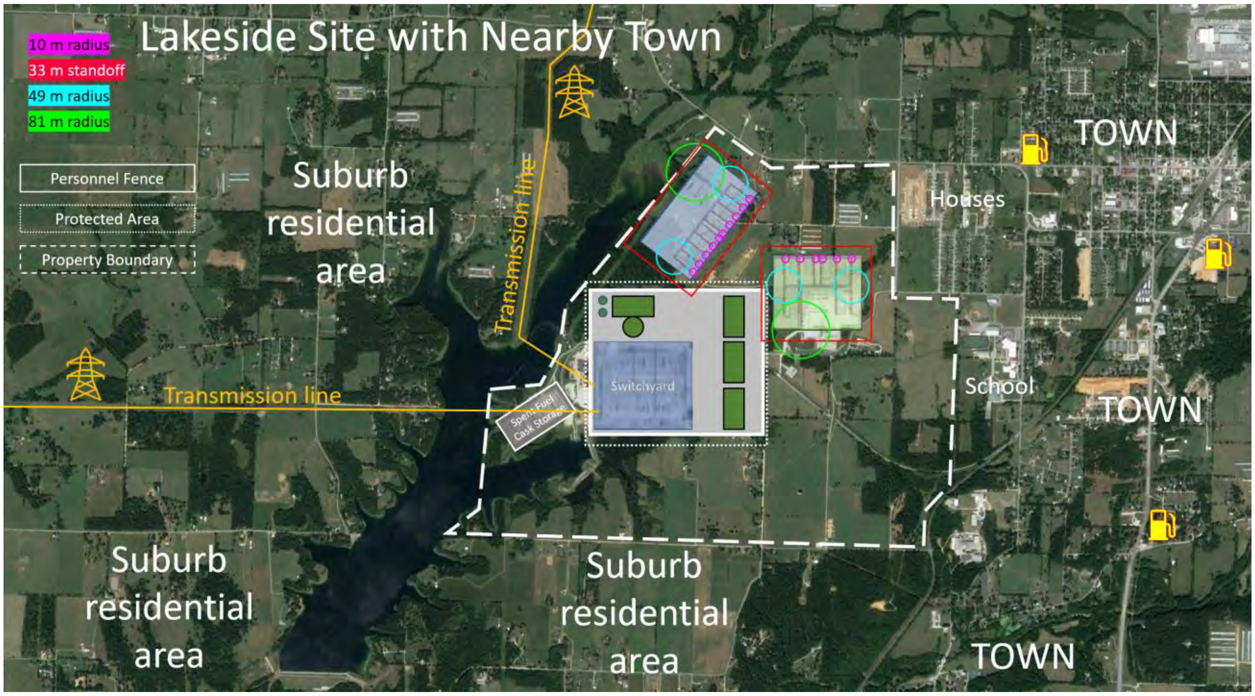


Figure 6-11. NRC RG-1.91 [11] Analysis for a 100 MW_{nom} HTEF of Site 3, "Town."

6.1.5.2 500 MW_{nom} High Temperature Electrolysis Facility Siting Analysis

The siting analysis for the 500 MW_{nom} HTEF was completed identically to the 100 MW_{nom} analysis except for the HTEF layout and the CPH. The HTEF layout for the 500 MW_{nom} analysis is shown in

Figure 4-2 and detailed further in Section 4. The high pressure CPH operates at 1500 psig just as the 100 MW$_{nom}$ facility, but because of the increased mass flow related to the increased power, the resultant minimum safety distance is larger. The minimum safety distance for the unprotected high pressure CPH section (Scenario 7 from [14]) by the Bauwens method is 530 m and by the TNT equivalence method as prescribed by NRC RG 1.91, Revision 3 [11] is 204 m. Annotated versions of the layouts are shown in Figure 6-12. For this report it is assumed that the high pressure CPH for the 500 MW$_{nom}$ facility has engineered barriers around it. The extended distances for an unprotected high pressure CPH are provided for safe siting information if the siting desired is to use the unprotected option.

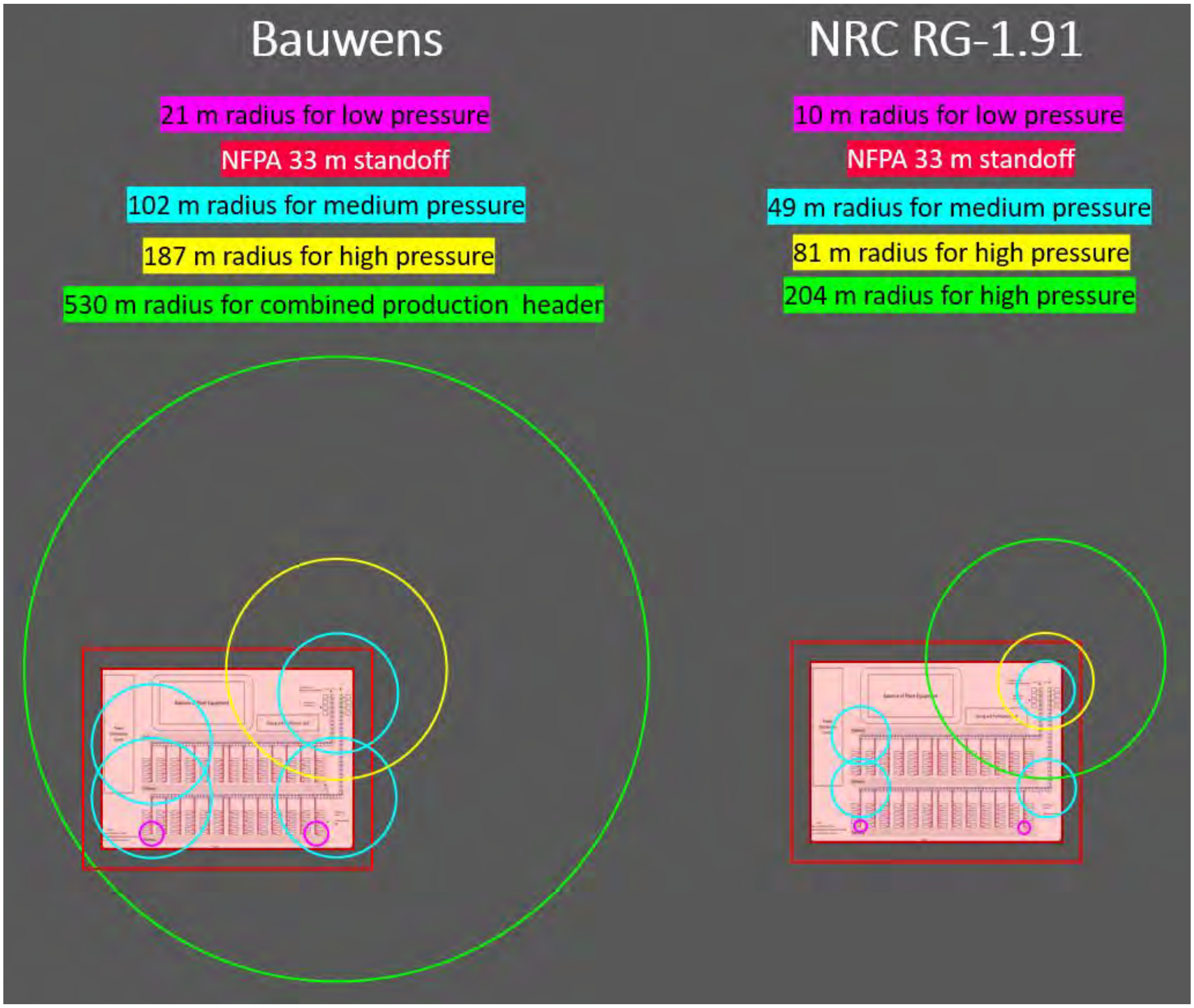


Figure 6-12. Plant layouts with imposed minimum safe distance radiuses and NFPA standoff for a 500 MW$_{nom}$ HTEF.

For Site 1 analysis of the 500 MW$_{nom}$ layout, the siting is still adjacent to the NPP without disturbing the transmission line or the transmission tower in the switchyard.

If it is desired to not use protection for the high pressure CPH, there is a significant increase in area of influence when looking at the minimum safe distance for each analysis. In the case of the Bauwens analysis (Figure 6-13) placement in the originally sited location for the 100 MW$_{nom}$ facility indicate that engineered barriers are required to attenuate pressure waves so the transmission lines would not experience overpressures greater than 0.16 psi. The NRC RG-1.91 [11] analysis, Figure 6-14, is less conservative and allows for the same siting as the 100 MW_{nom} facility without the need for engineered barriers.

Figure 6-13. Bauwens Analysis for a 500 MW_{nom} HTEF of Site 1, “Riverside with wetlands.”

Figure 6-14. NRC RG-1.91 [11] Analysis for a 500 MW_{nom} HTEF of Site 1, "Riverside with wetlands."

For Site 2 analysis of the 500 MW_{nom} layout, there is one site option that can still be within the protected area, if desired. All three site options illustrated are still near the NPP without disturbing the transmission line or the transmission tower in the switchyard or requiring engineered barriers beyond the one assumed to be around the high pressure CPH. However, care must be taken in placement to not disturb the spent fuel cask storage.

For an unprotected CPH, the case of the Bauwens analysis (Figure 6-15) shows placement in the originally sited location for the 100 MW_{nom} facility require that engineered barriers to attenuate pressure waves so the spent fuel cask storage and NPP administration buildings would not experience overpressures greater than 0.16 psi. The NRC RG-1.91 [11] analysis (Figure 6-16) is less conservative and allows for the same siting as the 100 MW_{nom} facility without the need for engineered barriers. The 500 MW_{nom} layout still allows multiple options for placing the HTEF, one completely inside the protected area, so minimal modifications need to be made to the physical protection system.

Figure 6-15. Bauwens Analysis for a 500 MW$_{\text{nom}}$ HTEF of Site 2, “Desert.”

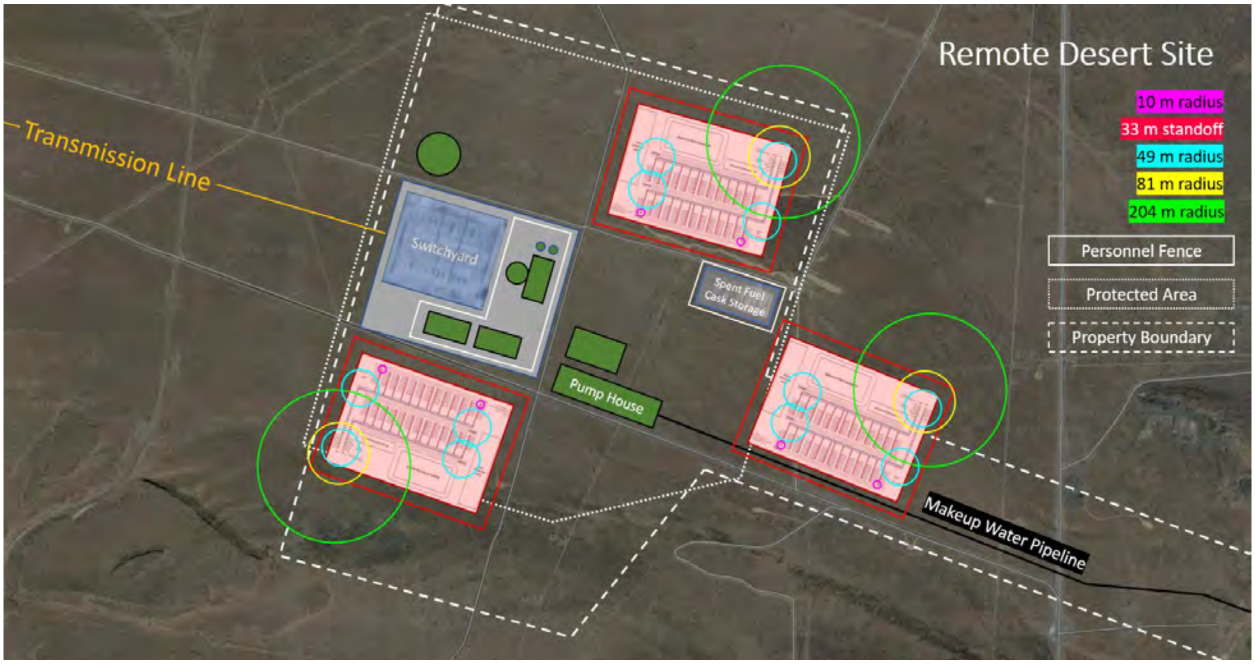


Figure 6-16. NRC RG-1.91 [11] Analysis for a 500 MW$_{\text{nom}}$ HTEF of Site 2, “Desert.”

For Site 3, the increased footprint limits the placement of the HTEF (Figure 6-17). With the default HTEF design shown, engineered barriers would be required non only on the CPH, but also at the high pressure section to protect plant support building windows. Re-design of the output position of the 500 MW$_{\text{nom}}$ HTEF’s CPH to a mid-plant position would allow for completely safe positioning, similar to the 1000 MWnom illustration in Figure 6-25.

For an unprotected CPH, the increased footprint and area of influence from the minimum safe distance of the high pressure header requires the use of engineered barriers to protect the NPP infrastructure as well as the surrounding town. In the Bauwens analysis in Figure 6-17, significant engineered barriers on all sides would be required to attenuate the pressure waves below 0.16 psi to protect the NPP infrastructure and surrounding residential and school buildings. In the NRC RG-1.91 [11] analysis in Figure 6-18, less engineered barriers would be required since only some surrounding town areas would be affected, but the enlarged footprint may require acquiring more property and extending the protected area.

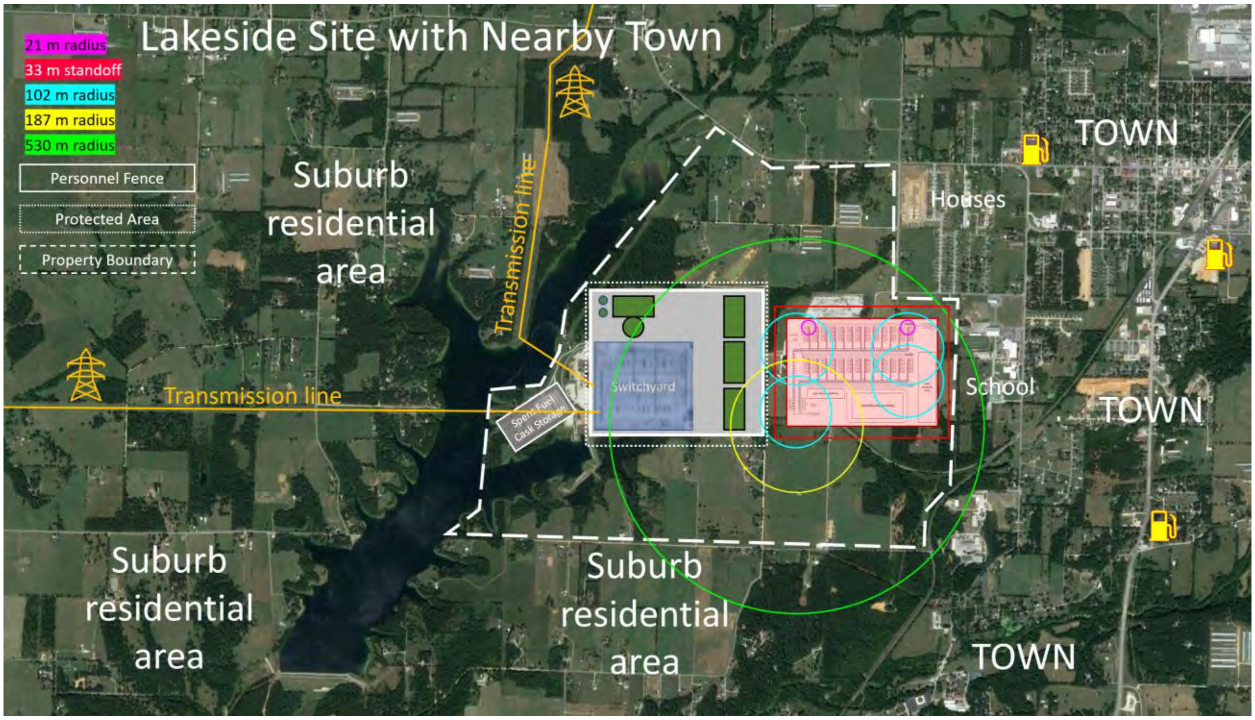


Figure 6-17. Bauwens Analysis for a 500 MW$_{nom}$ HTEF of Site 3, “Town.”

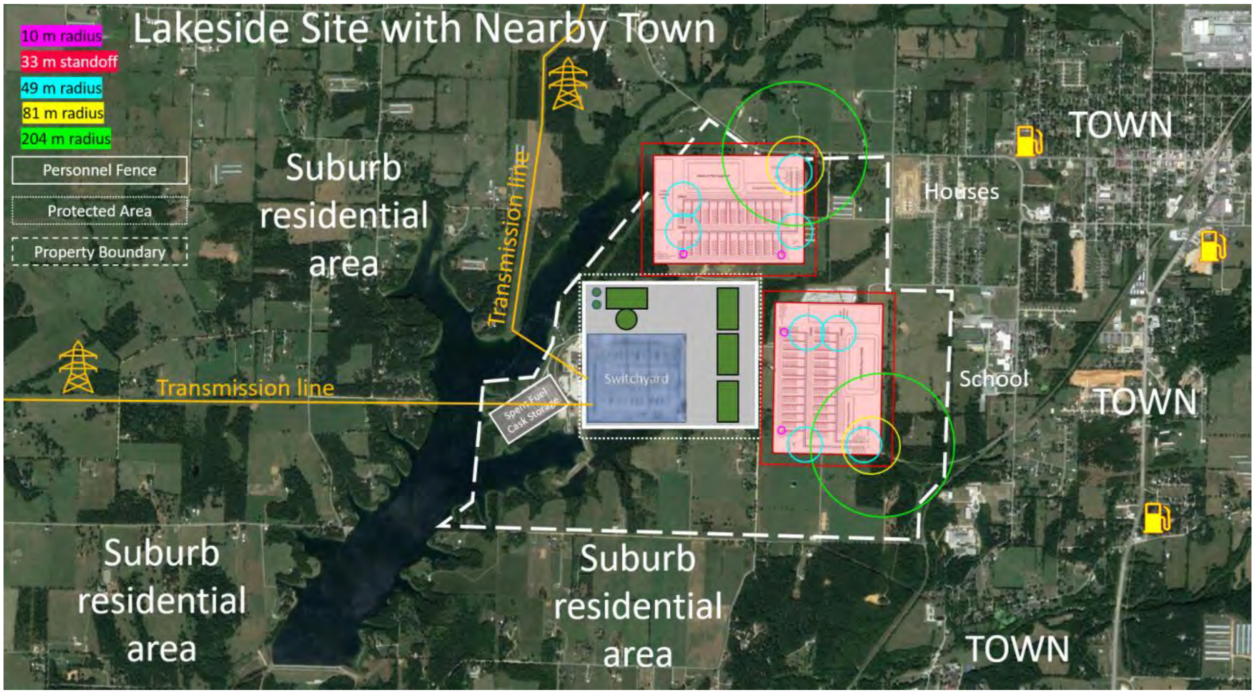


Figure 6-18, NRC RG-1.91 [11] Analysis for a 500 MW$_{nom}$ HTEF of Site 3, “Town.”

6.1.5.3 1000 MW$_{nom}$ High Temperature Electrolysis Facility Siting Analysis

The siting analysis for the 1000 MW$_{nom}$ HTEF was completed identically to the 500 MW$_{nom}$ HTEF analysis except for the footprint and high pressure CPH. The footprint is doubled as detailed in Section 4 and the 1000 MW$_{nom}$ system is two adjacent 500 MW$_{nom}$ systems that feed the same CPH. The high pressure CPH operates at 1500 psig just as the 100 and 500 MW$_{nom}$ facilities, but because of the increased mass flow related to the increased power, the resultant minimum safety distance is larger. The minimum safety distance for the high pressure section (Scenario 8 from [14]) by the Bauwens method is 681 m (Figure 6-19) and by the TNT equivalence method as prescribed by NRC RG 1.91 [11] is 252 m (Figure 6-20). For this report it is assumed that the high pressure CPH for the 500 MWnom facility has engineered barriers around it. The extended distances for an unprotected high pressure CPH are provided for safe siting information if the siting desired is to use the unprotected option.

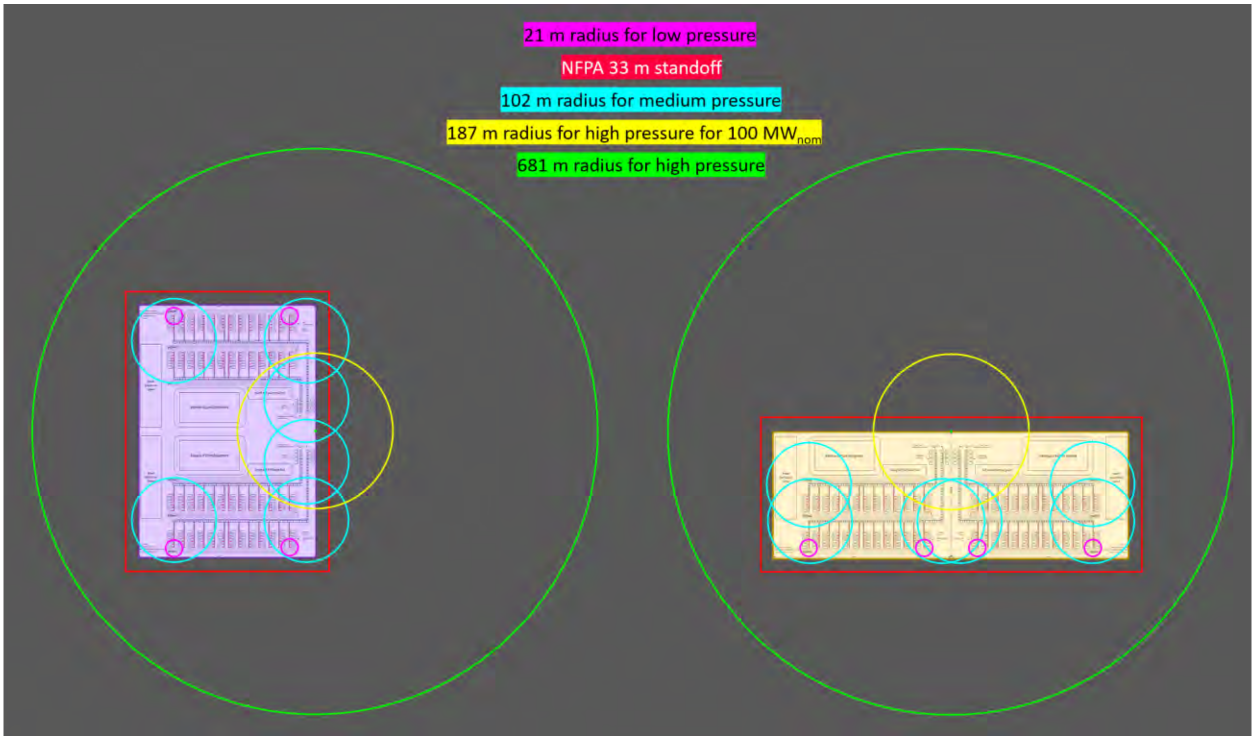


Figure 6-19. Plant layouts for a 1000 MW_{nom} HTEF with imposed minimum safe distance radiuses and NFPA standoff distances using the Bauwens method.

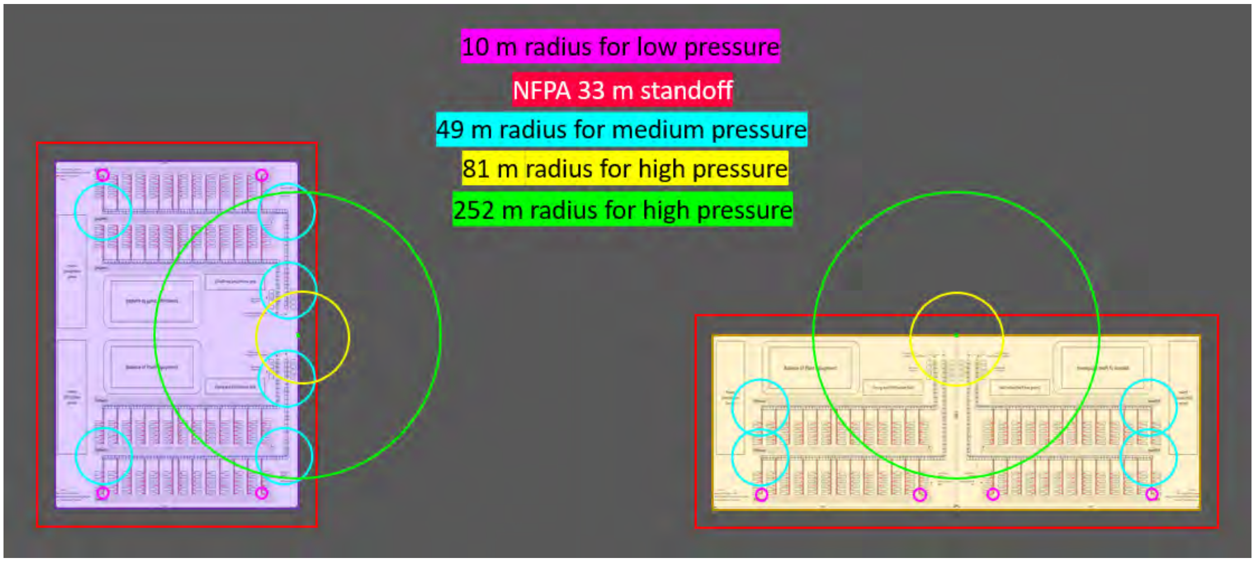


Figure 6-20. Plant layouts for a 1000 MW_{nom} HTEF with imposed minimum safety distance radiuses and NFPA standoff distances using the TNT equivalence method for satisfying NRC RG-1.91 [11].

For Site 1 analysis of the 1000 MW_{nom} layout, the siting is still adjacent to the NPP without disturbing the transmission line or the transmission tower in the switchyard.

If it is desired to not use protection for the high pressure CPH, there is again a significant increase in area of influence for the high pressure CPH when looking at the minimum safe distance for each analysis.

In the case of the Bauwens analysis (Figure 6-21), placement in the originally sited location for the 100 MW$_{nom}$ facility indicate that engineered barriers are required to attenuate pressure waves so the transmission lines, the NPP switchyard, the administration buildings, and the spent fuel cask storage would not experience overpressures greater than 0.16 psi. The NRC RG-1.91 [11] analysis (Figure 6-22) is less conservative because of the prescribed 1.0 psi standoff distance and allows for the same siting as the 100 MW$_{nom}$ facility using the long and narrow footprint without the need for engineered barriers.

Figure 6-21. Bauwens Analysis for a 1000 MW$_{nom}$ HTEF of Site 1, "Riverside with wetlands."

Figure 6-22. NRC RG-1.91 [11] Analysis for a 1000 MW_{nom} HTEF of Site 1, "Riverside with wetlands."

For Site 2 analysis of the 1000 MWnom layout, there is no site option that can still be within the protected area, but there are some options to be within the plant property boundary. One option is shown near the NPP without disturbing the transmission line or the transmission tower in the switchyard or requiring engineered barriers beyond the one assumed to be around the high pressure CPH.

For an unprotected CPH, in the case of the Bauwens analysis (Figure 6-23), placement near one of the originally sited locations for the 100 MW_{nom} facility indicate that engineered barriers are required to attenuate pressure waves so the spent fuel cask storage would not experience overpressures greater than 0.16 psi. The NRC RG-1.91 [11] analysis of a lengthwise side-by-side configuration of two 500 MW_{nom} HTEFs (Figure 6-24) is less conservative because of the 1.0 psi standoff distance and does not require engineered barriers.

Both illustrated HTEF sites mostly fit within the existing boundaries and therefore would require minimal adjustment to the physical protection system.

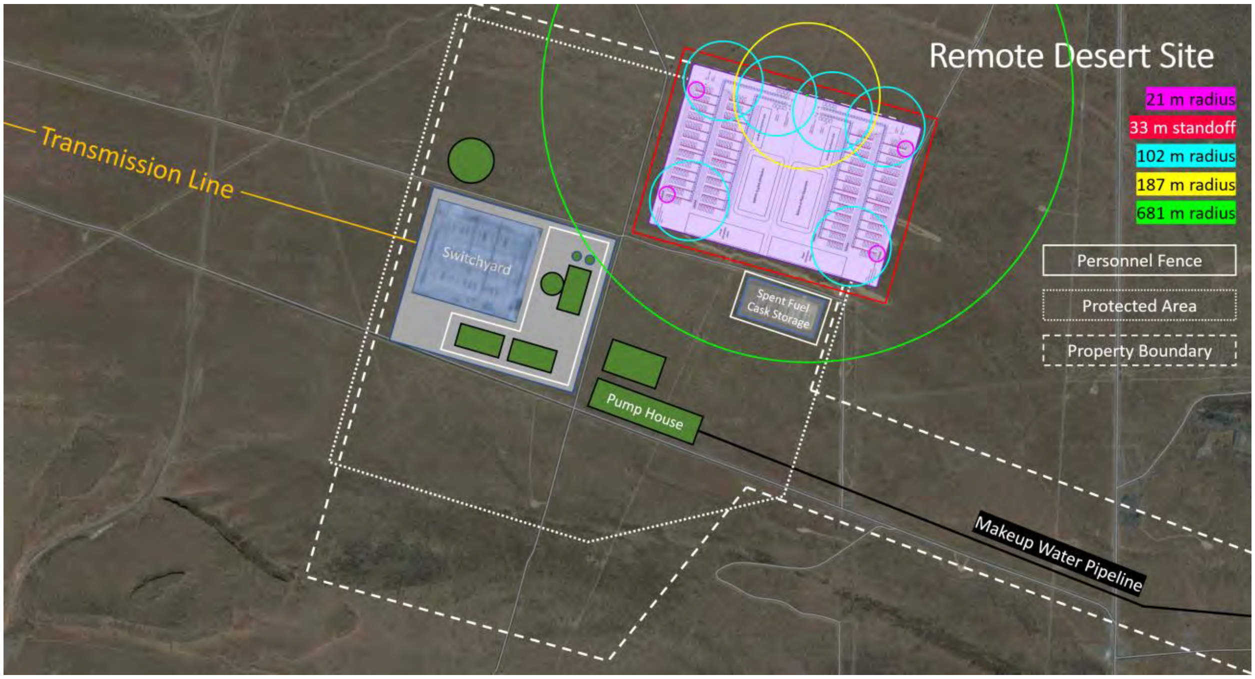


Figure 6-23. Bauwens Analysis for a 1000 MW_{nom} HTEF of Site 2, "Desert."

Figure 6-24. NRC RG-1.91 [11] Analysis for a 1000 MW_{nom} HTEF of Site 2, "Desert."

For Site 3, the increased footprint amazingly fits within the plant owned boundary. Engineered barriers are not required except for the CPH because of the centralized location of the high pressure section.

For an unprotected CPH, the conservatism of the analysis yields significantly different results. In the Bauwens analysis (Figure 6-25) the greatly increased area of influence from the minimum safe distance of the high pressure header requires with certainty the use of engineered barriers to protect the NPP infrastructure as well as the surrounding town. In the NRC RG-1.91 [11] analysis in Figure 6-26, engineered barriers would be required only if desired to protect surrounding NPP support buildings.

Both illustrated HTEF sites fit within the existing plant owned land.

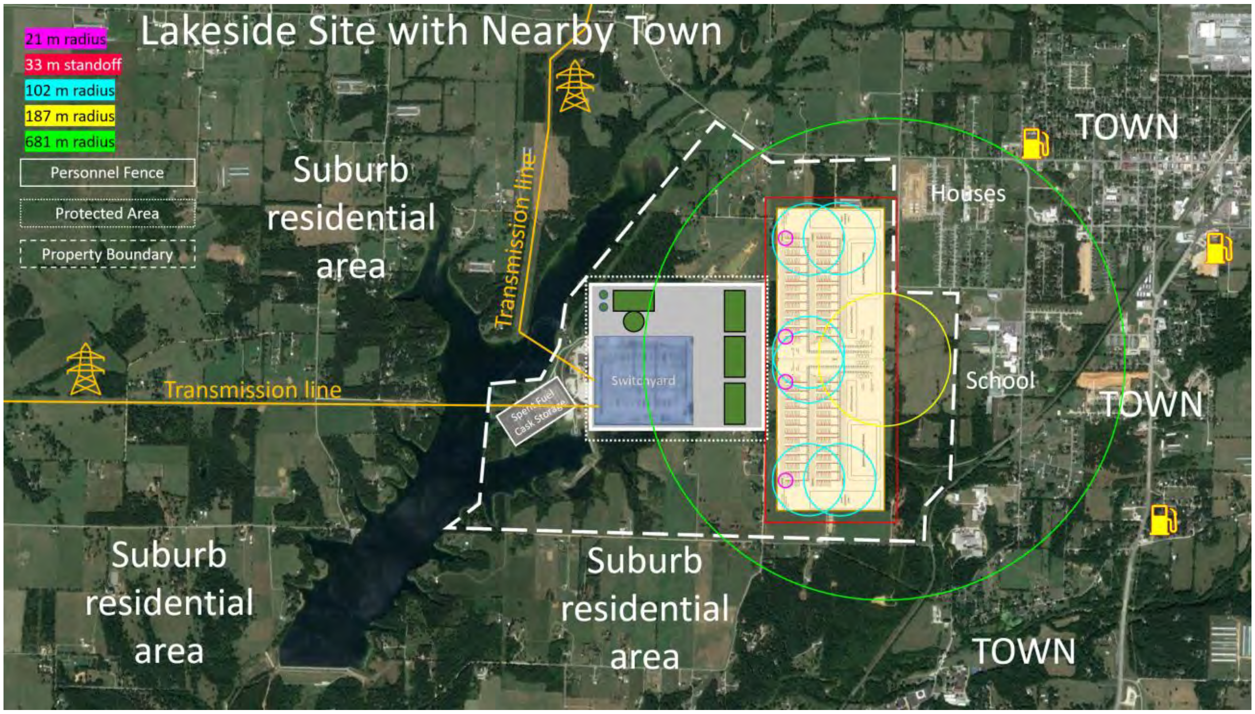


Figure 6-25. Bauwens Analysis for a 1000 MW_{nom} HTEF of Site 32, “Town.”

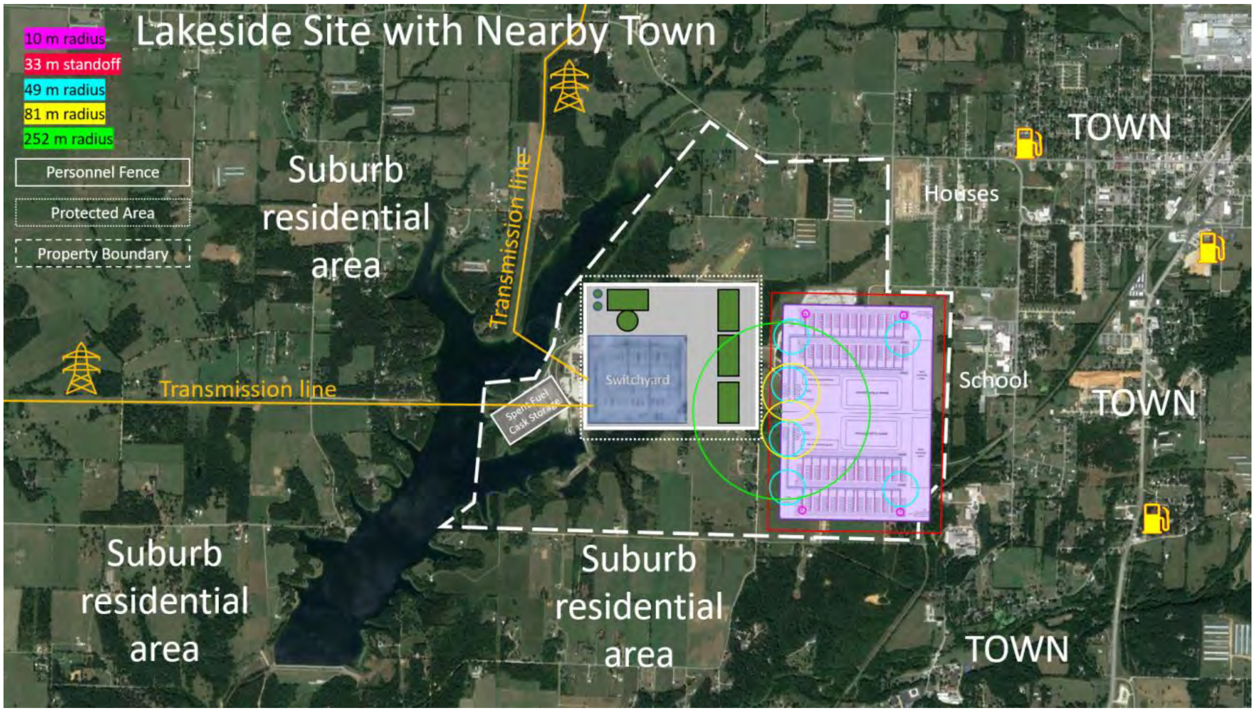


Figure 6-26. NRC RG-1.91 [11] Analysis for a 100 MW_{nom} HTEF of Site 3, “Town.”

6.1.5.4 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 HTEF. The design of this connection is described in Section 5.2 and illustrated in Figure 5-7. Most notably, the main turbine generator of the NPP is directly linked to the HTEF to provide electricity. If there is an overcurrent event at the HTEF, it could damage the turbine generator if the protections such as circuit breakers fail to isolate the generator.

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 6-12.

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 6-13. 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. The best data available for circuit breakers and relays were found in a report that did not explicitly provide fragility constants but provided a fragility curve instead. Values at the seismic bins utilized in this model (Table 6-12) were extracted from the curve and are reported in Table 6-13. 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 6-12. Extracted probabilities for high voltage circuit breakers and transformers [20]

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 6-13. Seismic fragility constants used for high voltage relays, busbars, and switchgear

Component Type	**Fragility Constants**			**Source**
	Am (g)	**βr**	**βu**	
Relay	0.9	0.35	0.37	[18]
Busbar	1.476	βc = 0.438		[19]
Switchgear	1.5	0.32	0.48	[18]

6.1.6 Standoff Distance Sensitivity Study

This section explores the impact of distance on the increase in the design basis event of LOOP. Nominal standoff distance is determined by the point at which the fragility of the switchyard transmission tower is at zero (0.16 psi).

The safe separation distance was detailed in Section 6.1.5 as summarized in Table 6-8. The safe distance using Bauwens method in that Table is defined as the distance where the switchyard fragility due to overpressure from a hydrogen jet-detonation drops to zero. This subsection explains why such a definition was chosen.

Section 9 talks about the regulatory criteria for licensing the addition of an HTEF into an NPP. The limiting criterion as discussed in the Section is the maximum threshold of a 10% increase of any IE [36][37]. The distance of HTEF from the switchyard affects the loss of offsite power initiator frequency. As shown in Figure 7-20, the increase in this frequency may be caused by a hydrogen jet or a cloud detonation event. However, the frequency of a cloud detonation is 6 orders of magnitude lower than the initial LOOP frequency (Section 6.1.4.2.2) and is therefore effectively probabilistically screened out. The limiting event for an increase in LOOP frequency is therefore the hydrogen jet detonation event.

The initial LOOP frequency as shown in Figure 6-27 and listed in Section 8 is 1.34E-2/year. The 10% increase in frequency for this event is therefore 1.34E-3, which becomes the maximum threshold for the jet detonation event. By substituting the leak frequency denoted as IE-LOOPSC-JET-HES3 in Figure 7-20, with the values listed in subsection 6.1.4.1, the fragility value (IE-LOOPSC-SC-JET-F) and its corresponding separation distance are found as plotted in Figure 6-27. It shows that the required fragility value is close to zero, and therefore the difference in separation distance between the 10% initiator criterion and the zero fragility criterion is relatively inconsequential at only less than 3 meters. As the HTEF size increases, its leak frequency increases and therefore the required fragility value must decrease further to meet the 10% frequency criterion. For that reason, the fragility value gets closer to zero as the HTEF size increases. With this negligible difference, it is reasonable to settle for the separation distance where the fragility drops to zero. There is no need to fine-tune inches of separation distance for a HTEF facility having the size of several acres.

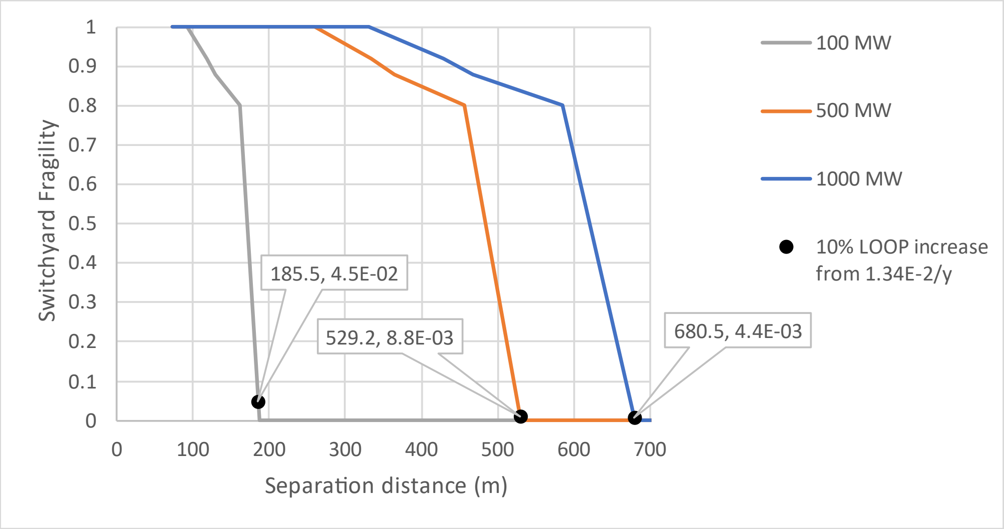


Figure 6-27. Switchyard fragility as a function of separation distance.

6.1.7 Toppling of Stacked SOEC Modules due to High Winds

SOEC modules will be stacked to optimize space so the HTEF facility may be installed within or close to the nuclear facility's plant owned and possibly withing the protected area. Stacking SOECs has not been evaluated in detail yet, but may be feasible because an SOEC module is planned to be housed in a container that is based on a stackable standard shipping container as shown in Figure 6-28. An immediate hazard consideration that comes to mind regarding such a vertical configuration would be the toppling of the containers due to hurricanes or high winds. The toppling of an SOEC module may cause hydrogen leakage, steam leakage and electrical disturbances, and economic losses due to damage to the SOEC modules. These are unwanted outcomes, which may be quantified considering the likelihood of the external initiator, its stress level, and the strength of the container fastening structures.

Figure 6-28. Shipping container as an SOEC's sealed enclosure (left) [24] and an open enclosure (right) [25].

This subsection provides an initial deterministic analysis of the high wind hazard to HTEF facilities with vertically stacked SOEC modules. According to the American Society of Civil Engineers (ASCE) standard [26], the HTEF facility falls into a Risk Category III structure. Structures in this risk category must be designed to withstand certain loads including wind loads. We gathered the wind annual exceedance probabilities for all the NPPs in the United States using the ASCE7 hazard tool [27]. The most conservative wind data among those sites is shown in Figure 6-29, with the maximum wind speed a Risk Category III structure must withstand is highlighted in red (183 mph). Despite the conservatism, the frequency of this wind speed is a relatively low 5.9E-4/year.

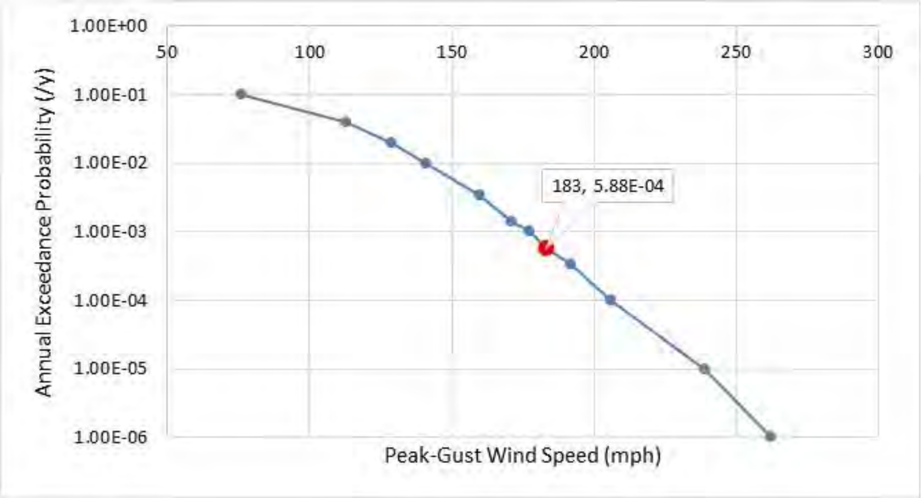


Figure 6-29. Conservative high wind frequencies

The SOEC container measures 52 ft × 8 ft × 8.5 ft. Therefore, the highest wind stress is on the 52 ft × 8 feet surface. Assuming the sea level atmospheric density of 1225 g/m3, a 183 mph wind gust will exert a force of 158 MN on the container's surface. It is a large force, which is reasonable considering that a 183 mph wind falls within the highest category of the Saffir-Simpson hurricane wind scale [28], and the container's surface area is large. Assuming the top SOEC container is fastened to the bottom SOEC container with a bolt on each of its four corners, the shear force experienced by each bolt is 39.6 MN. Since the fastening consists of only two flat surfaces, the bolt shear mechanism is a single shear. The average single shear stress experienced by each bolt is calculated by dividing the shear force with the bolt's surface area [29]. The average single shear stress as a function of bolt's diameter is plotted in Figure 6-30. The Fastenal design support reference [30] provides the guideline for bolt's shear strength as 60% of the ultimate tensile strength for common carbon steels with hardness up to 40 HRC (Rockwell hardness scale), which corresponds to a generic value of 90,000 psi or 620 Mpa. This shear strength limit is plotted in the figure below. It shows that the fastening bolts need to be at least 1 ft in diameter for the stacked SOEC containers to meet ASCE7 standard for a Risk Category III structure. It is physically unlikely to use such large bolts on shipping containers. However, smaller sized bolts may be justified when we consider the low statistical likelihood of this wind speed at about once in every 1,700 years. In addition, this justification may also be supported with other engineering features, such as adding more fastening points, engineered wind barriers, or using an open-frame SOEC design as pictured in Figure 6-28.

It is assumed that the HTEF manufacturer using stacked SOECs will use similar analysis to prevent this hazard based upon the site the HTEF will be built.

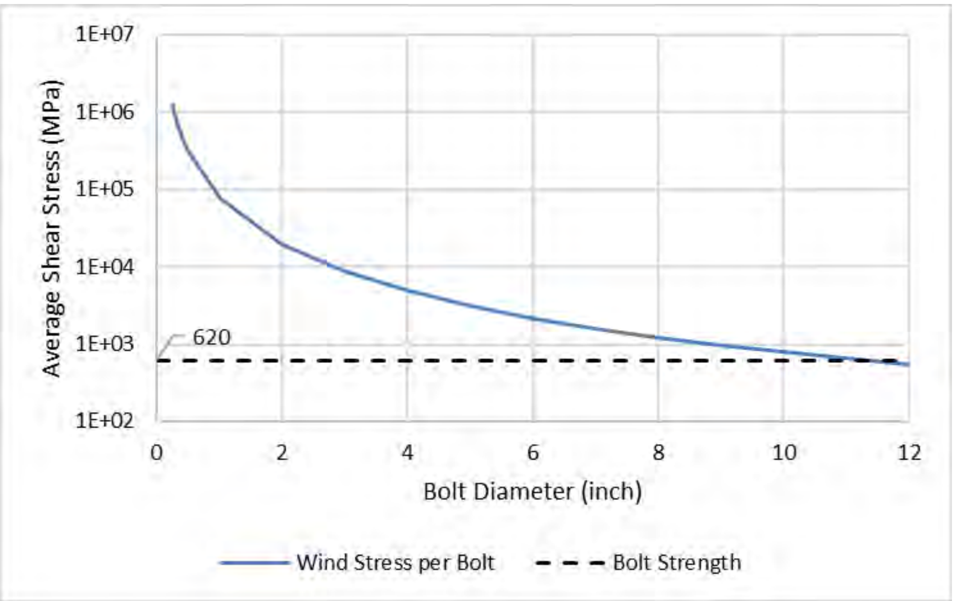


Figure 6-30. Shear stress caused by high winds to SOEC container's bolts versus bolt's average strength.

6.1.8 Hydrogen storage tank leak and detonation

Storage of 1000 kg of compressed gas hydrogen can be accomplished with one tank. Much like the pressurized pipes analyzed in Section 6.1.4.2 there are two possible detonation scenarios stemming from hydrogen leakage from a storage tank: a high-pressure jet detonation and a cloud detonation.

The high-pressure jet detonation occurs from a relatively small leak from the inlet/outlet valve of the tank up to and including a full bore rupture. The size of the tank is not of concern with this scenario because the tank pressure is assumed to be 1500 psi and the only parameter that changes is the length of time of the detonation potential. Time was not considered in the prior analyses and is not considered in this analysis. It is assumed that if it leaks it has a single probability of detonation. As shown in Table 6-14 the results of SNL's analysis using the Bauwens method determined that the distance for a high-pressure jet detonation to cause a 0.16 psi overpressure is 23 meters [14]. This is approximately equivalent to the safe distance noted for the low pressure sections of the 1000 MW_{nom} HTEF (Section 6.1.5.3).

Table 6-14. 1000 kg hydrogen storage tank high-pressure jet detonation overpressure versus distance

Pressure (psi)	Distance (m)
0.1	32
0.16	23
0.2	20
1.0	8

The cloud detonation would result from a tank shear followed by a detonation of the rapidly escaping gas cloud. This has been postulated and empirically tested by SNL. The event would involve an industrial accident or intentional act of terrorism. The industrial accident would require equipment such as a forklift to shear the tank and a detonation source. The closest accident found in a search of accident databases was a propane tank that had been punctured by a forklift resulting in a fire, not a detonation. A frequency of this type of accident could be determined based on the one event and conservatively assuming it would always cause the cloud detonation. Acts of terrorism are not as predictable probabilistically and have not been considered elsewhere in this report other than in some FMEA questions in the appendices.

While the cloud detonation of a shear event of a hydrogen tank has been caused empirically on smaller tanks, a model has not been made to date to evaluate the overpressure versus distance of a 1000 kg hydrogen storage tank. It is for this reason that we recommend that the storage tank be shielded with engineered barriers despite the low safe standoff distance for the high-pressure jet leak detonation.

7. PROBABILISTIC RISK ASSESSMENT MODEL

7.1 Electrical Transmission Probabilistic Risk Assessment Model

A PRA model was created to evaluate the probability of a general plant transient occurring due to an overcurrent event damaging the turbine generator as seen at a high level in Figure 5-8. The frequency of this event would add on to the NPP's Transient IE frequency. This could occur three different ways according to the one-line diagram in Figure 5-7: the three-winding transformer at the H2 plant experiences an overcurrent and all circuit breakers fail to trip, the load at the 13.8-kV switchgear pulls too much current and all circuit breakers fail to trip, and the generator transformer experiences an overcurrent and the GCB fails to open and isolate the generator. For the transformers and circuit breakers between the transformers, the relay protection diagram was utilized, and the primary and backup relay were individually accounted for each breaker and transformer as their protection system. The failure data used for the relays came from the 2020 Industry Average Parameter Estimates by the NRC and INL which analyzed reactor protection system (RPS) studies data [31]. While this likely refers to low-voltage relays (125 VDC) utilized in RPSs, not high-voltage transmission, this was the best available data. For the switchgear for the H2 Island load, a failure for switchgear rated for over 5 kV was utilized. All other data used were sourced from the Institute of Electrical and Electronics Engineers (IEEE) Gold Book [32].

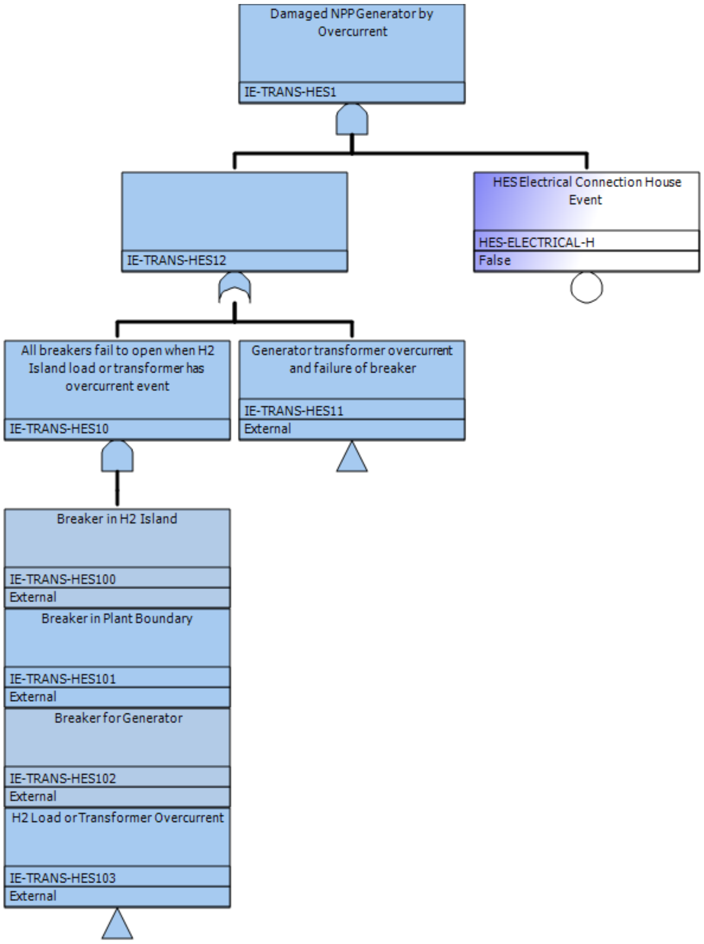


Figure 7-1. Overall FT (IE-TRANS-HES1).

All scenarios were considered in FT IE-TRANS-HES1 (Figure 7-1) indicating either a failure of the generator transformer overcurrent and failure of its breaker or all breakers failing to open when the hydrogen island load or transformer has an overcurrent event will lead to damage of the NPP generator. All breakers failing scenarios contain the circuit breakers located between the transformers that need to trip to protect the generator from overcurrent in either the transformer or the loads. These scenarios were modeled as sub FTs in AND gate IE-TRANS-HES10 (Figure 7-1). An application of a primary and backup relay for each breaker and transformer decreases the likelihood of failure along with the presence of the three breakers in series. As long as one of the breakers trips, the generator will be protected. Each of the subtrees representing the logic for the breakers are shown in Figure 7-2, Figure 7-3, and Figure 7-4. The subtree representing overcurrent in either the transformer or the loads is shown in Figure 7-5 with examples of what each A and B branch have in Figure 7-6 and Figure 7-7.

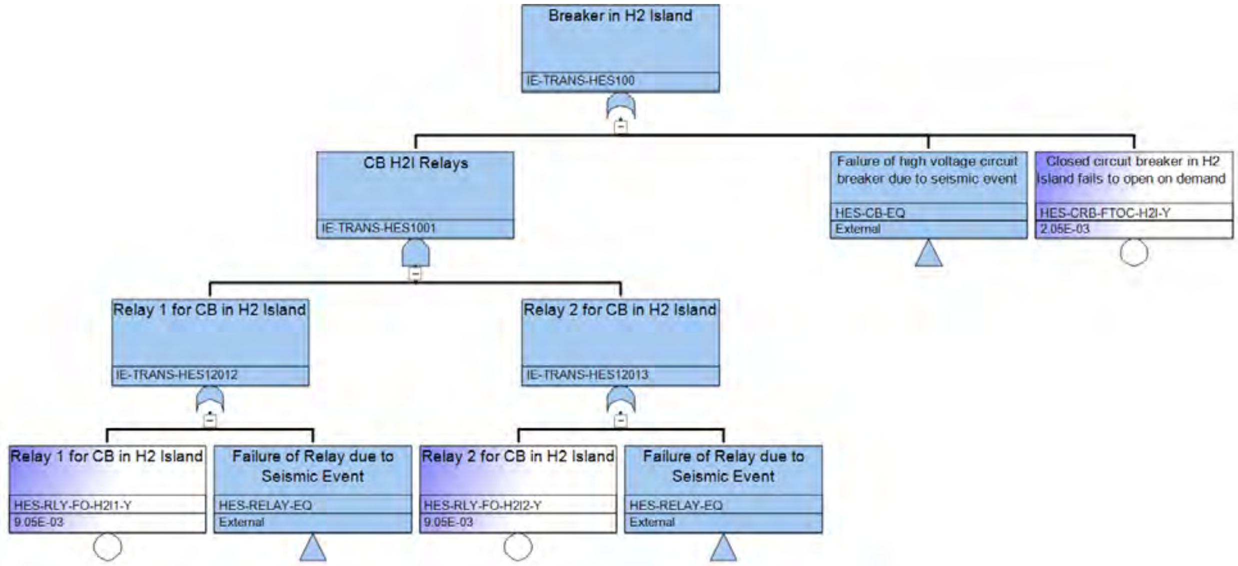


Figure 7-2. Breaker in H2 Island (IE-TRANS-HES100).

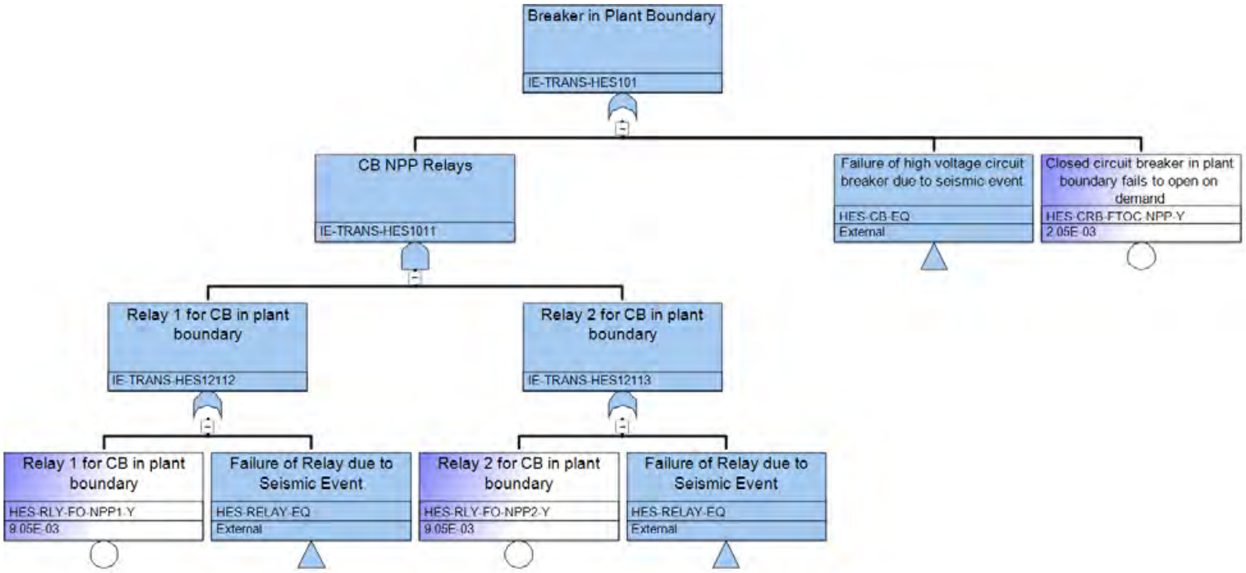


Figure 7-3. Breaker in Plant Boundary (IE-TRANS-HES101).

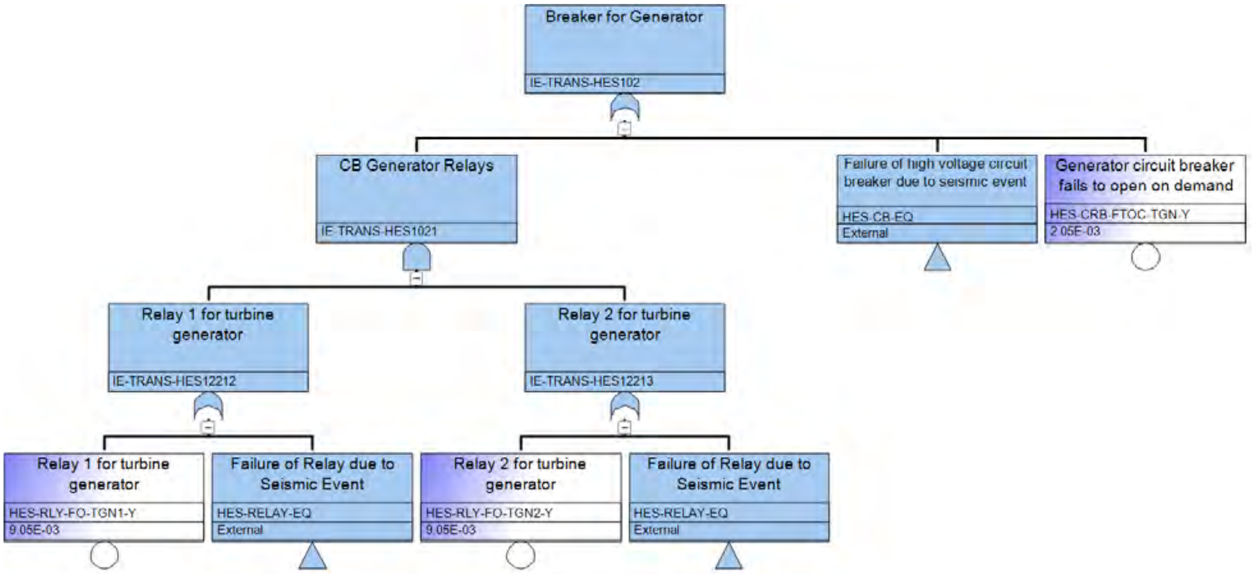


Figure 7-4. Breaker for Generator (IE-TRANS-HES102).

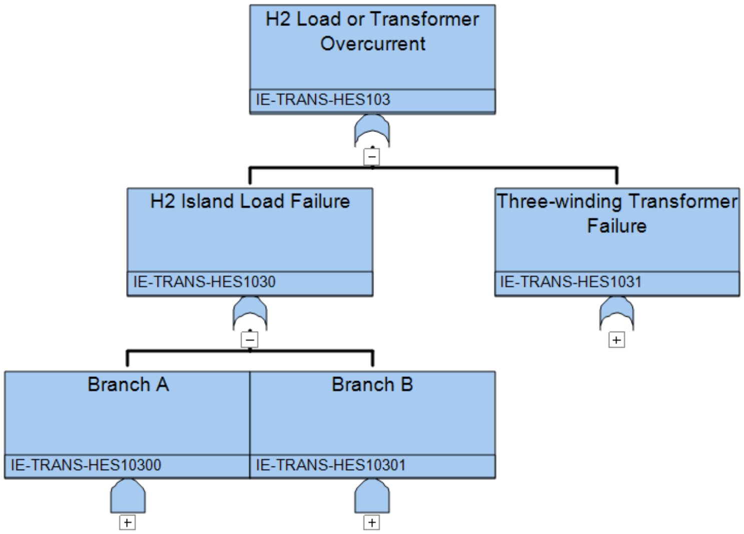


Figure 7-5. Overcurrent by H2 plant transformer or load expanded trees (IE-TRANS-HES103).

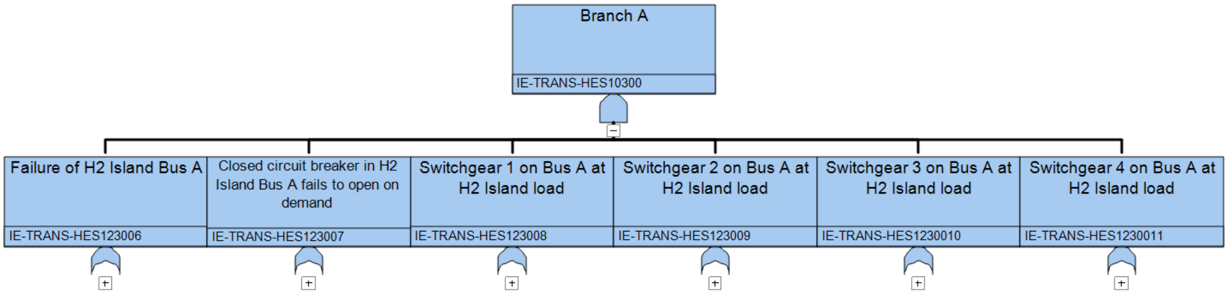


Figure 7-6. Example of a branch in H2 Island Load Failure: Branch A.

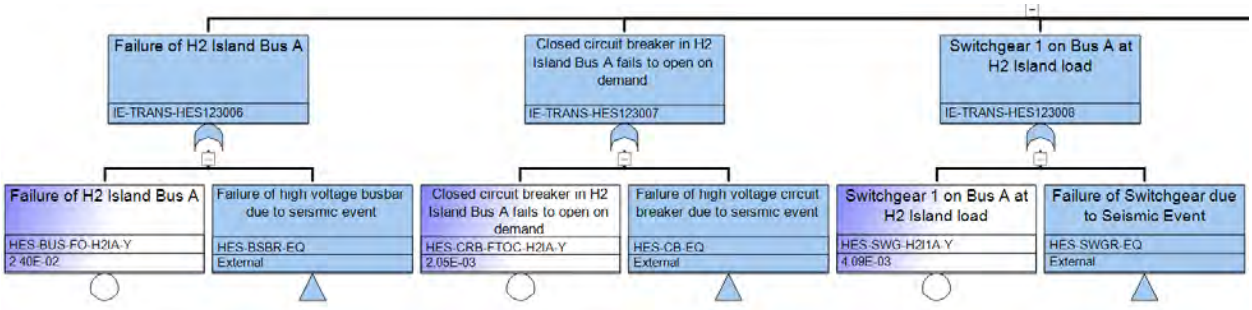


Figure 7-7. Example of Failure of H2 Island Bus, Closed circuit breaker in H2 Island Bus fails to open on demand, and Switchgear on Bus at H2 Island load for Branch A.

The third scenario (Figure 7-8) models the failure of the plant boundary breaker to trip under gate (Figure 7-9) and the occurrence of overcurrent at the generator transformer (Figure 7-10). Since only one circuit breaker separates the transformer from the generator, it is more likely that the generator will be damaged by this scenario. Although, just like the other breakers and transformer, the application of a primary and backup relay for each breaker and transformer decreases the likelihood of failure.

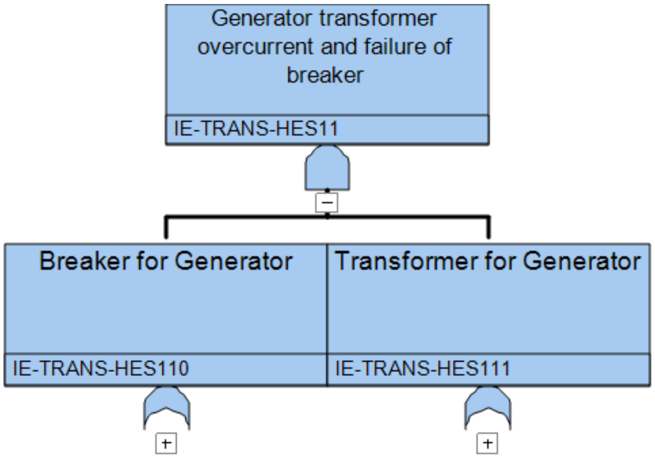


Figure 7-8. Overcurrent by generator step-up transformer.

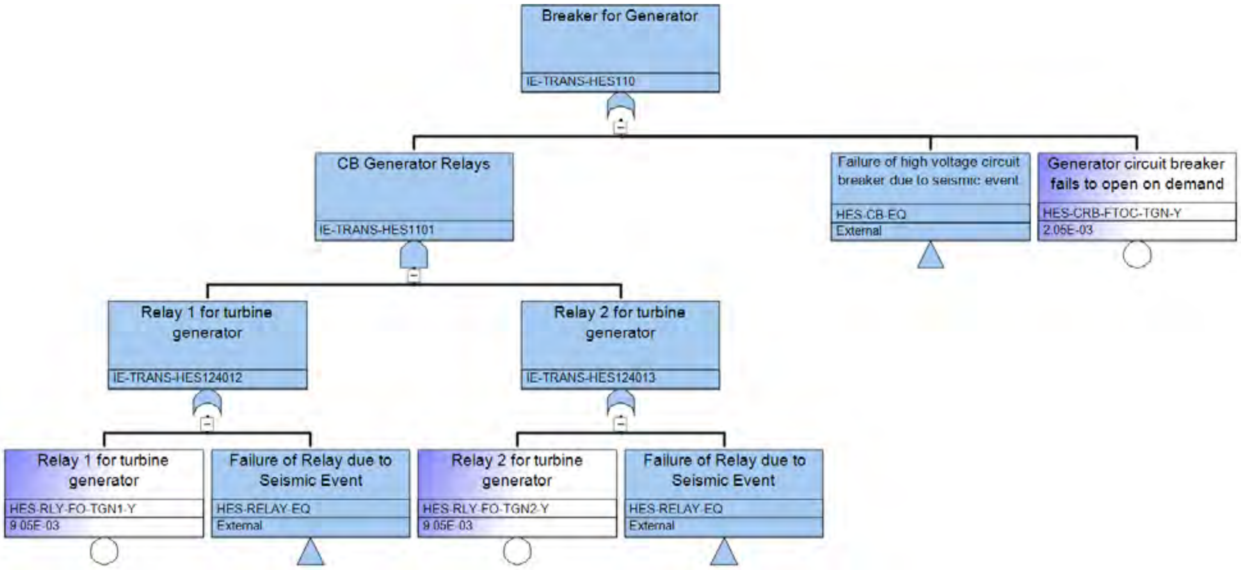


Figure 7-9. Breaker for generator (IE-TRANS-HES110).

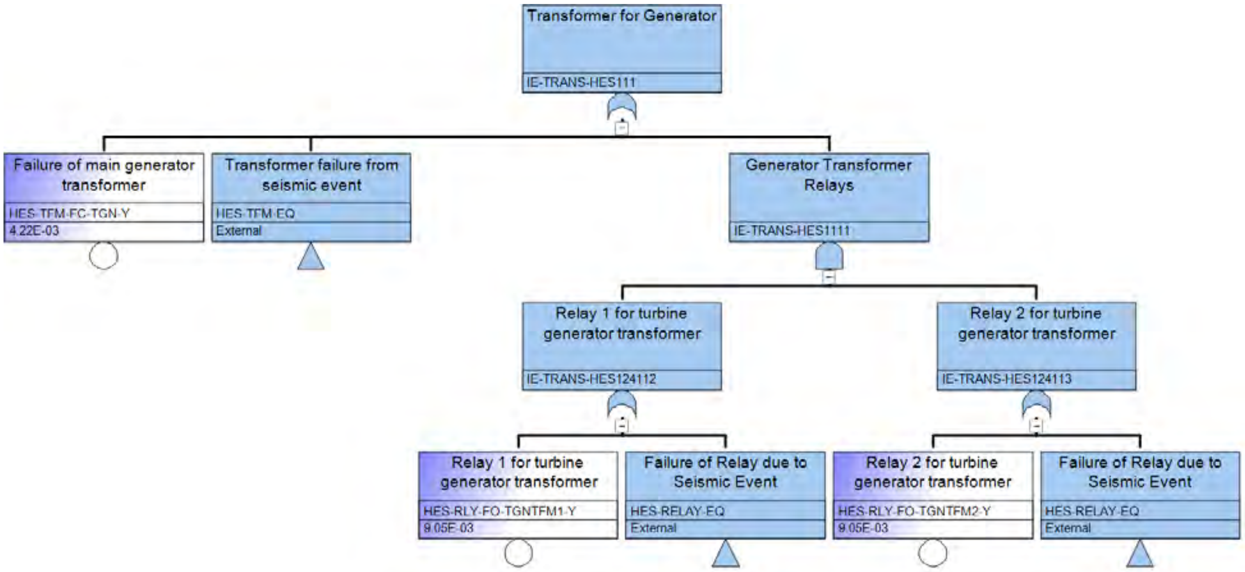


Figure 7-10. Transformer for generator (IE-TRANS-HES111).

No other scenarios needed to be considered as the report describing the pre-conceptual design [5] states in Section 4.3.5 that “The H2 production facility is physically and electrically separated from the offsite power circuits. Therefore, there is no impact to offsite power sources or plant safety loads, which normally are powered from offsite power sources.” The single line diagram (Figure 5-7) illustrates this further by showing that the offsite power sources are on a different bus than the turbine generator and line to the H2 production facility in a ring bus arrangement.

7.2 Generic Pressurized Water Reactor Model

The addition of an HES into the steam line creates more venues for the steam to leak out either through pipe breaks or component ruptures. Therefore, one of the possible hazards considered in this study is an increased probability for steam leakage through the new system. In this study, a two-loop generic PWR model is used as a reference. The ET for the Main Steam Line Break initiator is shown in

Figure 7-11. A break in the main steam line causes the loss of the ultimate heat sink and therefore the reactor must be tripped. The removal of reactor decay heat depends on whether steam generators are ruptured because of the steam line break. If steam generators are functioning, the auxiliary feedwater (AFW) system supplies feedwater to the steam generators while the main steam/feedwater line is isolated. If the main steam line cannot be isolated, the AFW system cannot inject water due to the high pressure in the line and the High Pressure Injection (HPI) is used in its place. In case the AFW system fails, the reactor heat is removed using the feed and bleed mechanism on the primary cooling line. The failure event of steam generators requires mitigation actions as prescribed in the Steam Generator Tube Rupture ET. Meanwhile, the failure of the reactor trip requires mitigation procedures laid out in the Anticipated Transient Without Scram (ATWS) Event Tree. These ETs are provided in Appendix A: Generic PWR PRA Model.

Additionally, the existence of a hydrogen production plant near the NPP may create a hydrogen detonation hazard. This detonation may cause significant blast pressure and missiles that may damage surrounding structures including the plant's switchyard components. The loss of switchyard components is assumed to trigger a LOOP event. This event has been taken into consideration in the PRA model as shown in Figure 7-13 for the nominal switchyard LOOP ET and Figure 7-14 for the LOOPSC ET with the HES installed. The LOOP IE trips the reactor and brings the emergency power online. The auxiliary feedwater system is then activated to maintain cooling on the secondary coolant loop. If the pressure-operated safety relief valves are closed and Reactor Coolant Pump (RCP) seal cooling is maintained, this mitigation action is sufficient to safely shut down the reactor. If RCP seal cooling fails, the mitigation procedure switches to the LOOP-1 Event Tree, shown in Figure 7-15. This procedure involves activating a controlled bleed-off in the primary cooling system while maintaining the reactor coolant subcooling. This action should prevent the RCP seal from failing due to overpressure and shuts down the reactor safely. If the RCP seal fails, the operator has 1 hour to recover power before the situation can be declared as a Medium-Size-Loss-of-Coolant-Accident. If power is recovered within that timeline, the operator can proceed with the HPI to make up the inventory of the primary cooling system until the reactor is brought to a safe shutdown state.

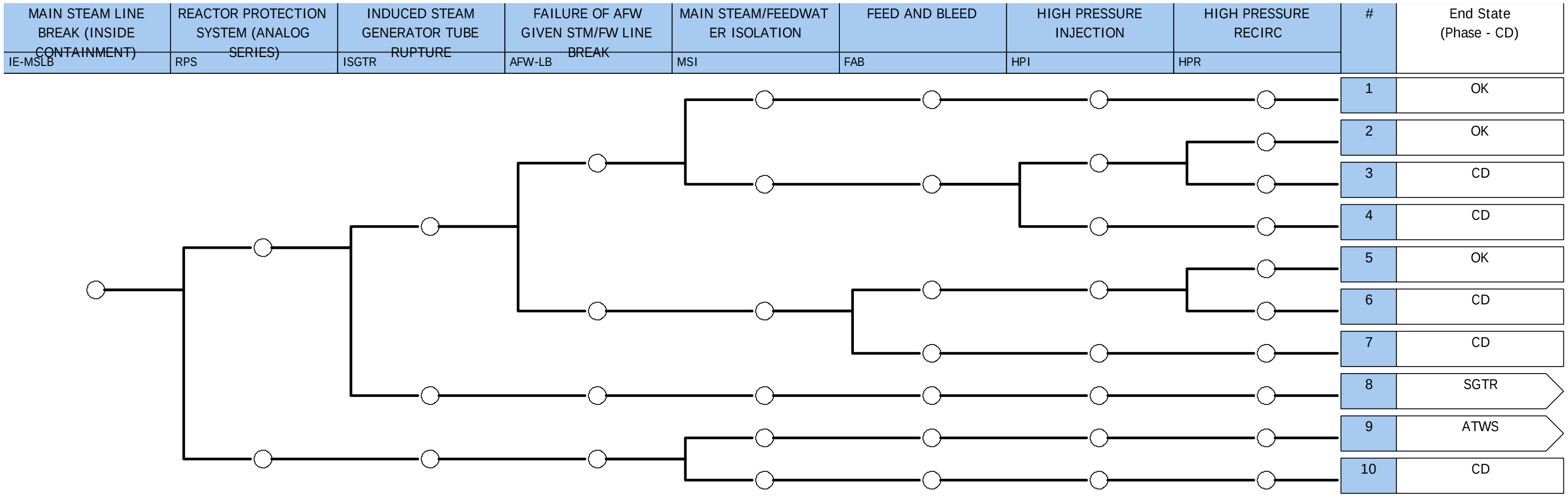


Figure 7-11. MSLB ET (IE-MSLB).

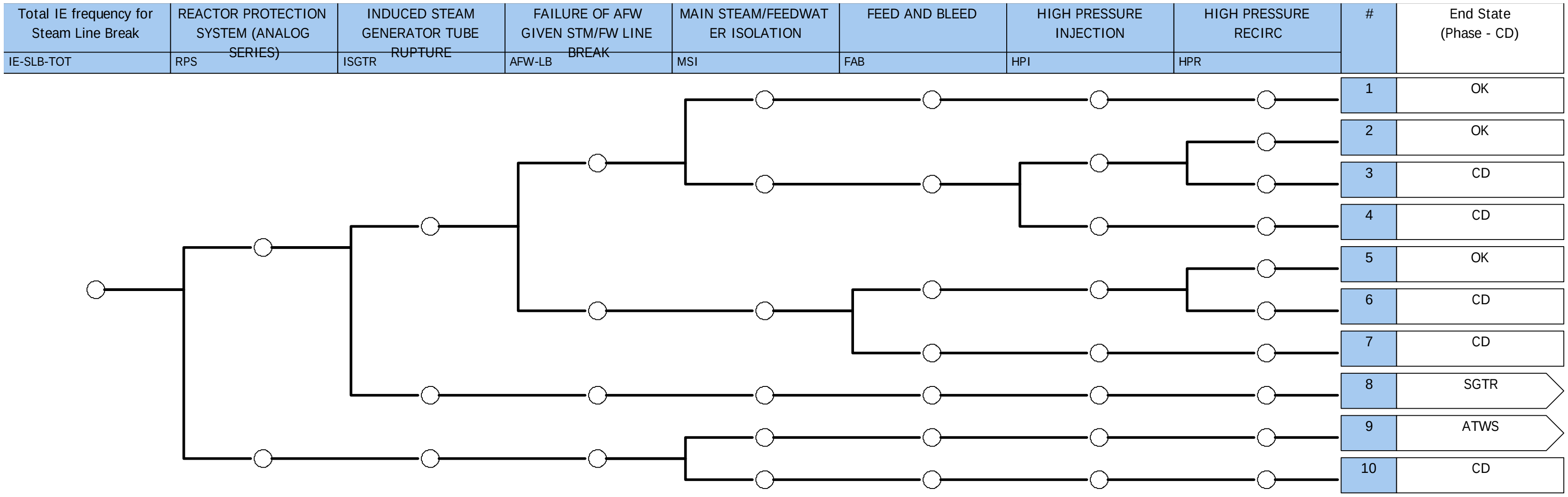


Figure 7-12. MSLB ET with HES (IE-SLB-TOT).

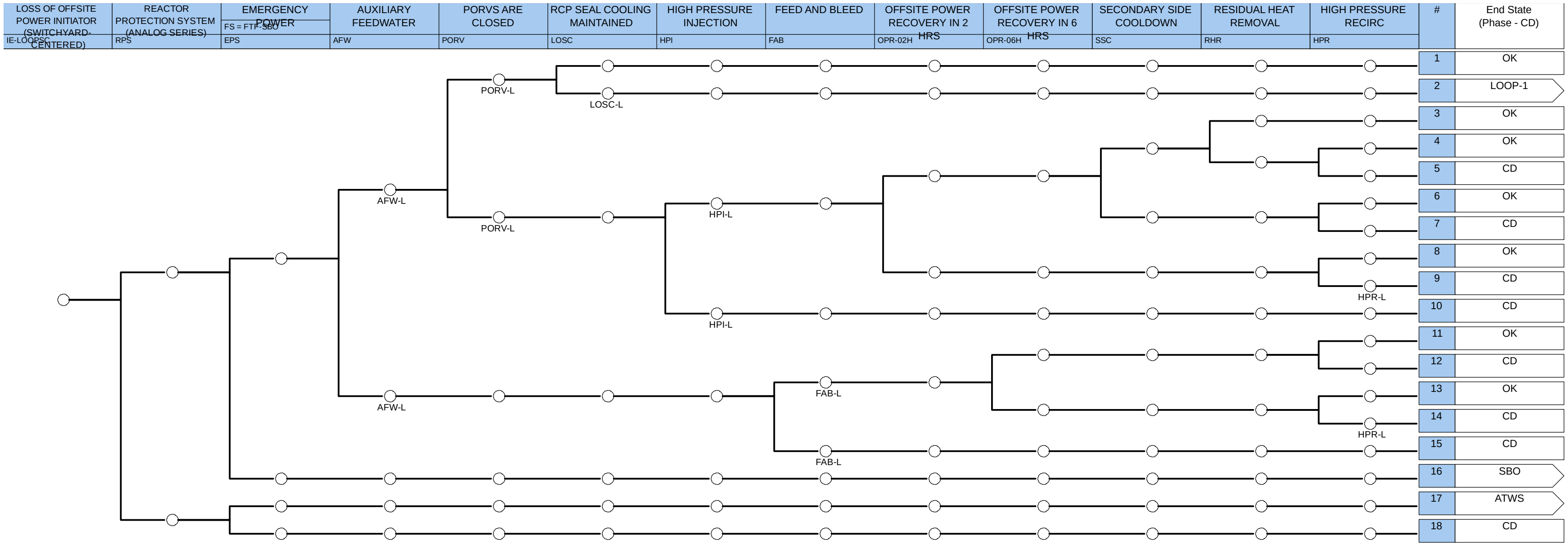


Figure 7-13. LOOPSC ET (IE-LOOPSC).

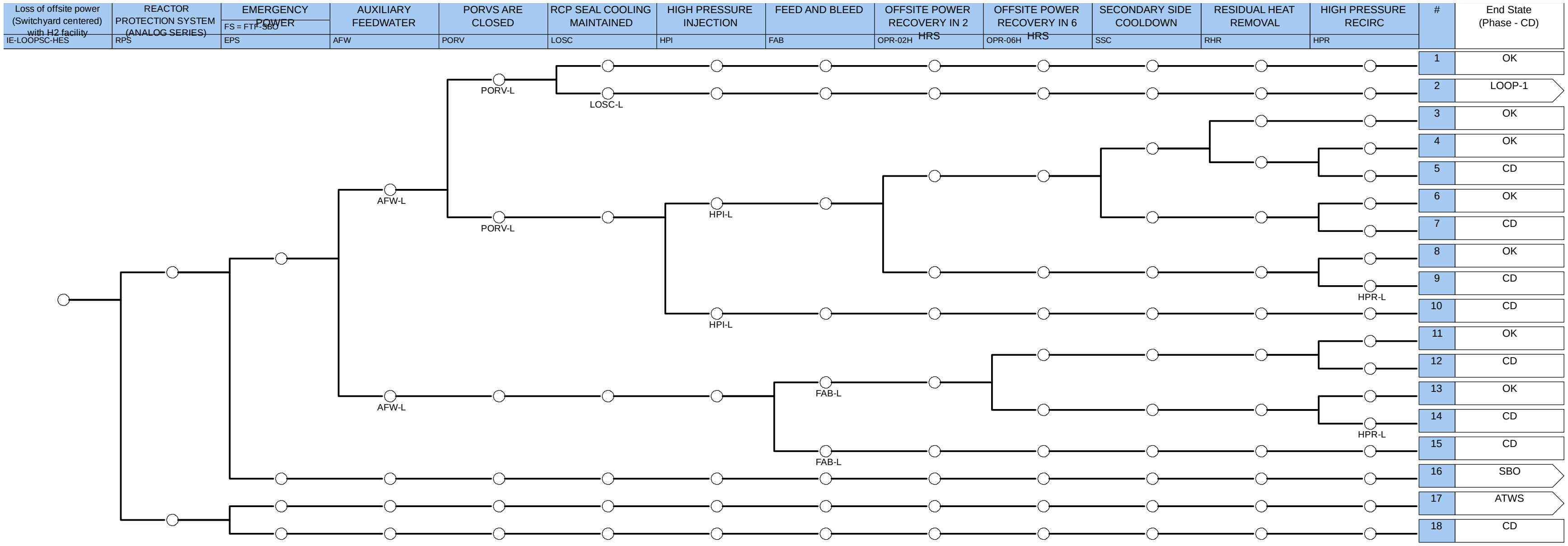


Figure 7-14. LOOPSC with HES ET (IE-LOOPSC-HES).

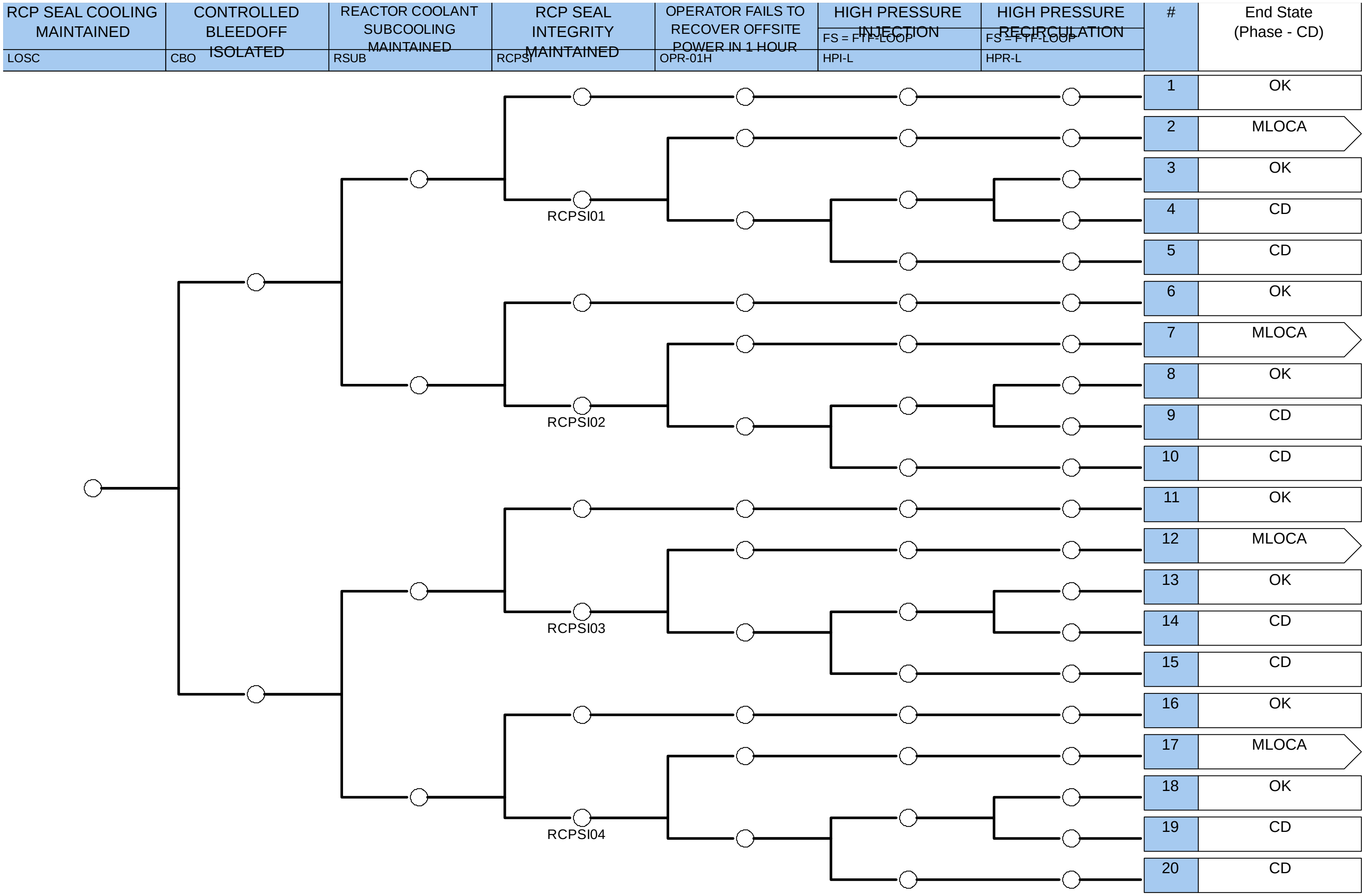


Figure 7-15. LOOP-1 ET (LOSC).

7.2.1 Heat extraction system linkage into the pressurized water reactor model

The addition of the HES that taps into the main steam line of a NPP creates additional points where steam may leak out of the secondary cooling loop. The additional frequency from HES is added to the existing base IE frequency of the steam line break ET using an IE FT as shown in Figure 7-16. The IE FT developed for the 100 MW HTEF design in Figure 5-2 is shown in Figure 7-17. Meanwhile, the FT developed for the 500 MW design in Figure 5-4 is shown in Figure 7-18, and the FT developed for the 1000 MW design in Figure 5-6 is shown in Figure 7-19. The top events of these trees add up to the total steam line break IE frequency, which is used as the initiator for the new steam line break ET as shown in Figure 7-12. House events are used to select which HTEF size is to be used in the FT quantification.

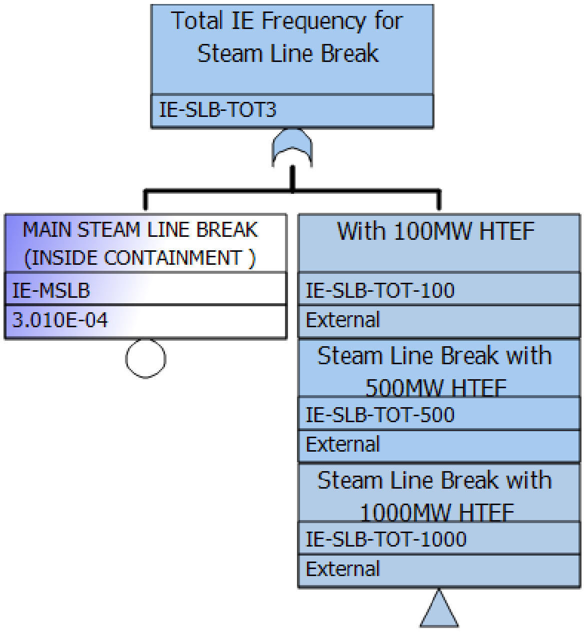


Figure 7-16. FT for total IE frequency for PWR MSLB.

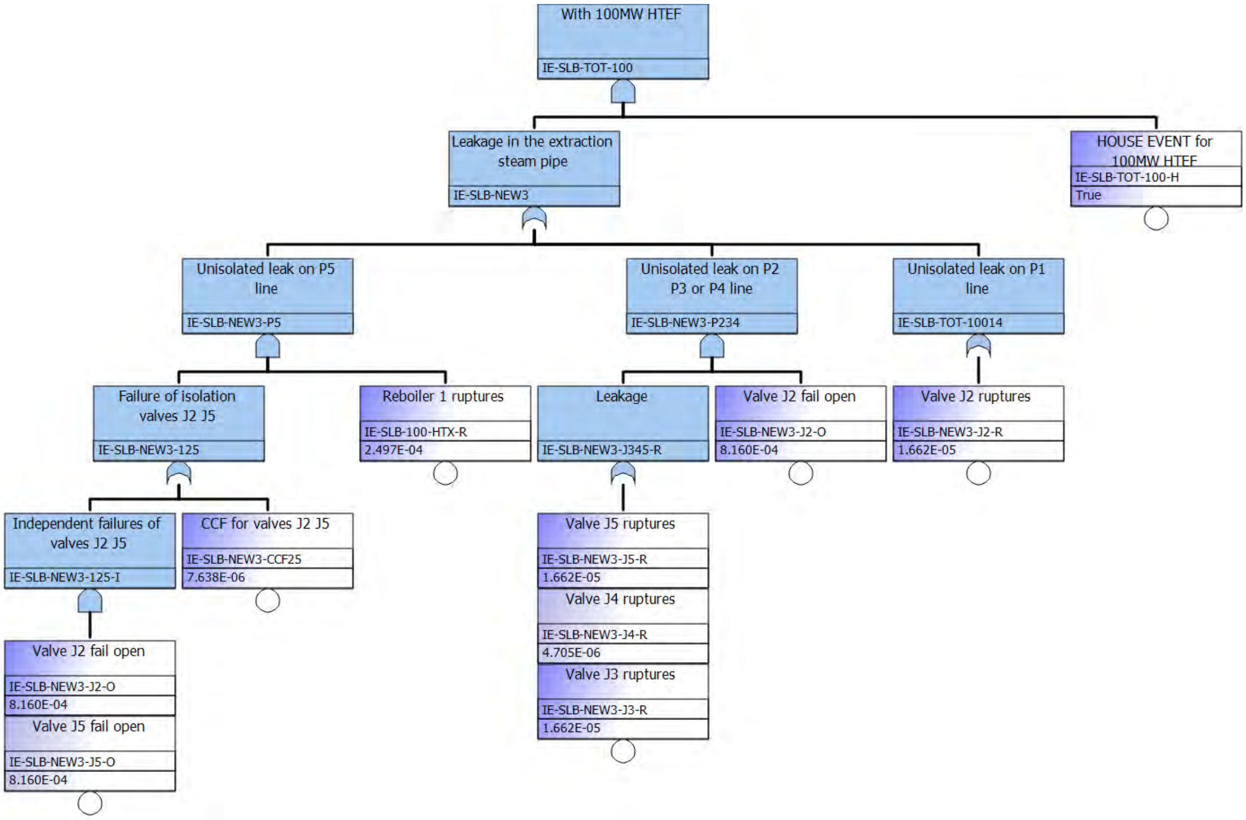


Figure 7-17. FT for Total Initiating Event frequency for MSLB with 100 MW HTEF.

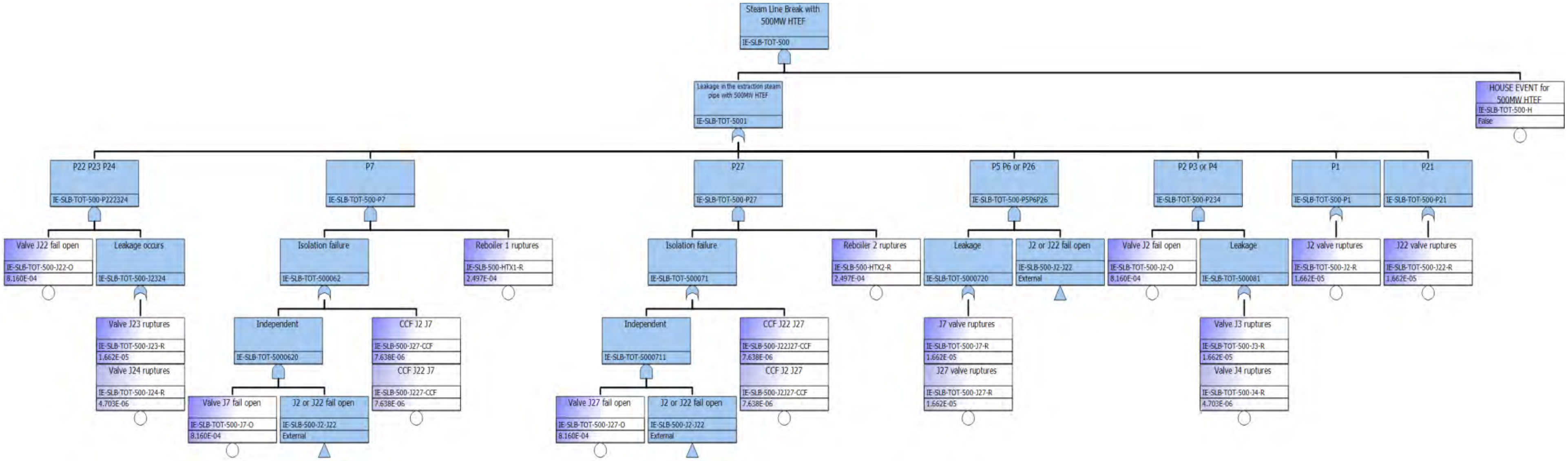


Figure 7-18. FT for Total Initiating Event frequency for MSLB with 500 MW HTEF.

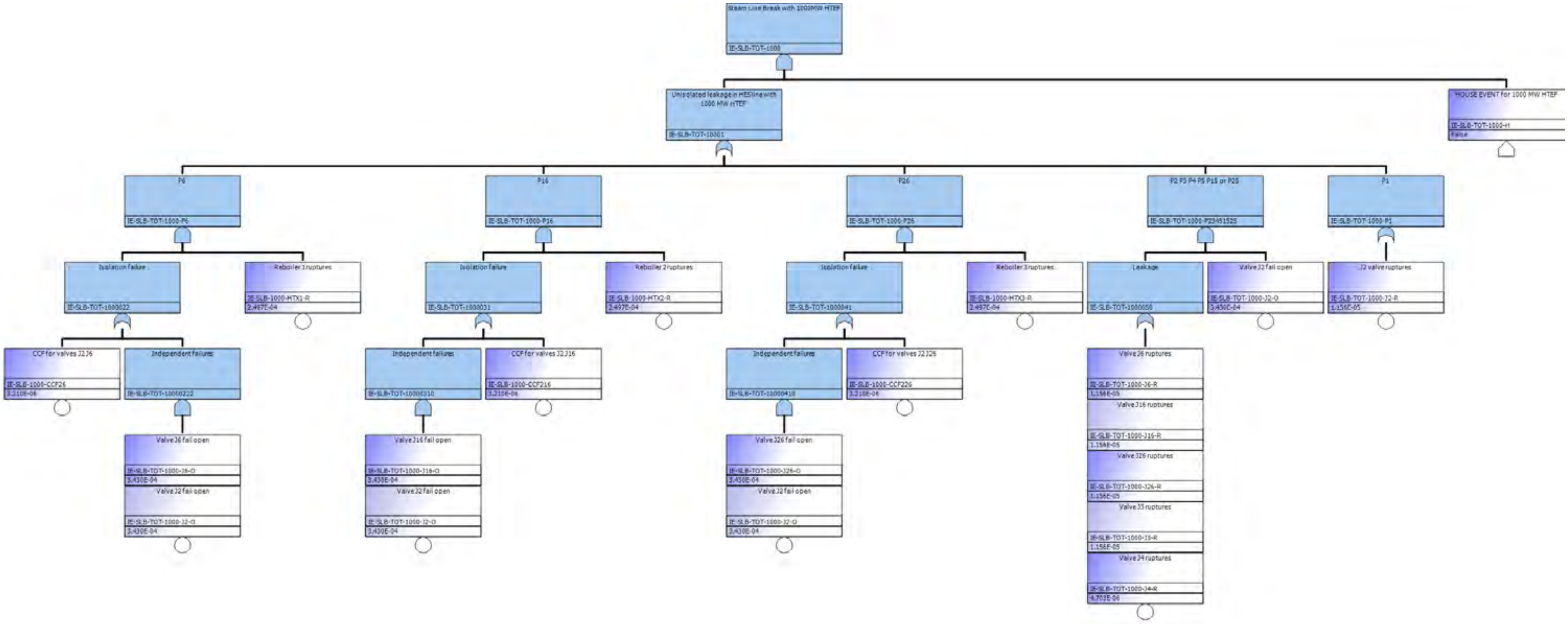


Figure 7-19. FT for Total Initiating Event frequency for MSLB with 1000 MW HTEF.

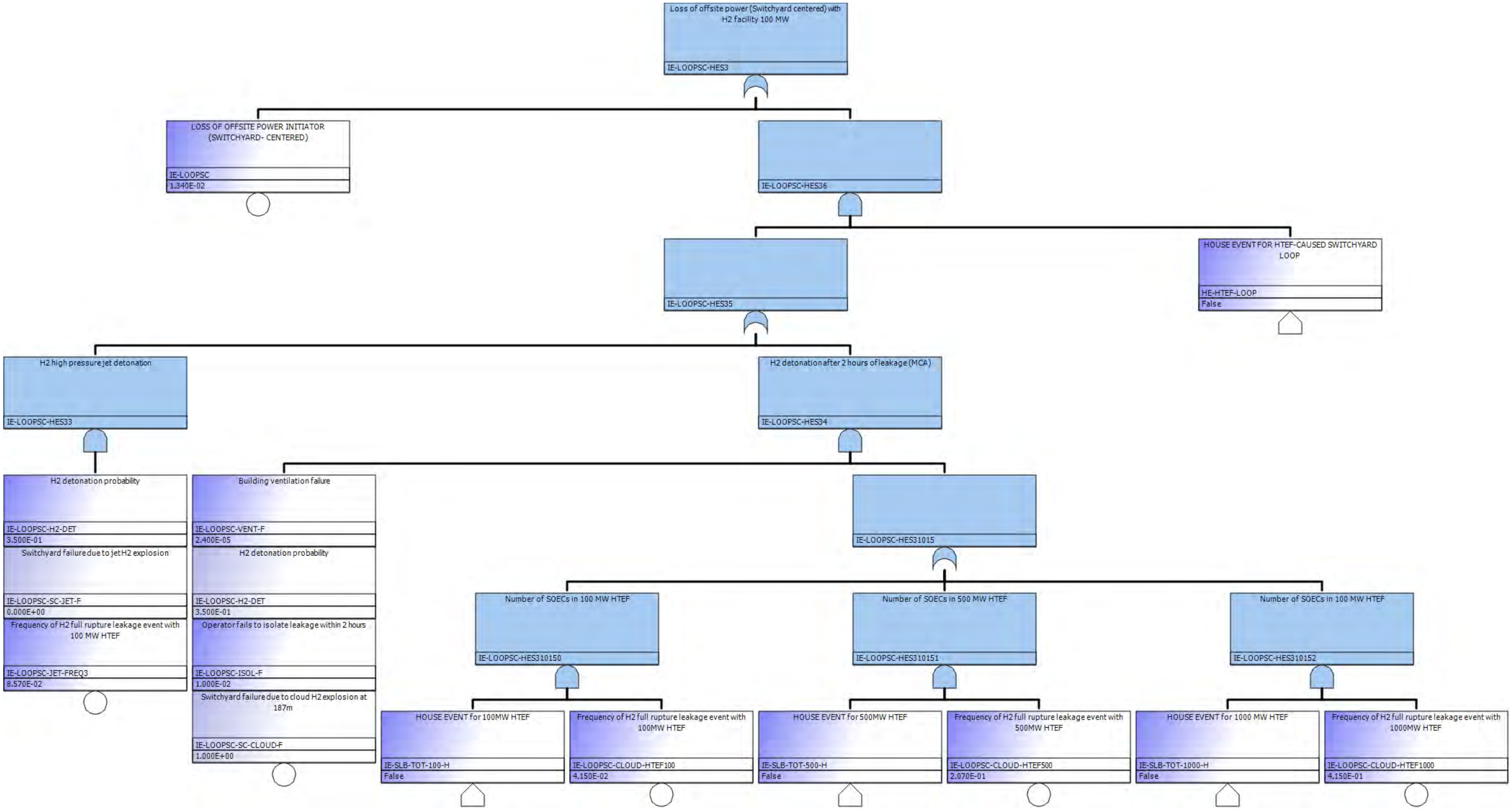


Figure 7-20. Total frequency of LOOP with Hydrogen Production Facility (IE-LOOPSC-HES).

7.3 Generic Boiling Water Reactor Model

Similar to the PWR, the HES in the BWR taps steam from the main steam line. A loss of the steam flow rate due to a leakage event in the HES may lead to a general transient event. The mitigation procedure for this event is shown in Figure 7-21. The transient can be mitigated safely if reactor power generation is shut down, the offsite power is available, the safety relief valves remain closed to preserve coolant inventory, and the power conversion system is running. If this power conversion system fails, the HPI system is activated followed by suppression pool cooling. Without the automatic suppression pool cooling, operators need to depressurize the reactor manually and perform the control rod drive injection. Further mitigation sequences can be deducted from the figure, in which various redundant measures are available including a low-pressure injection (LPI) system, shutdown cooling, containment spray, and containment venting.

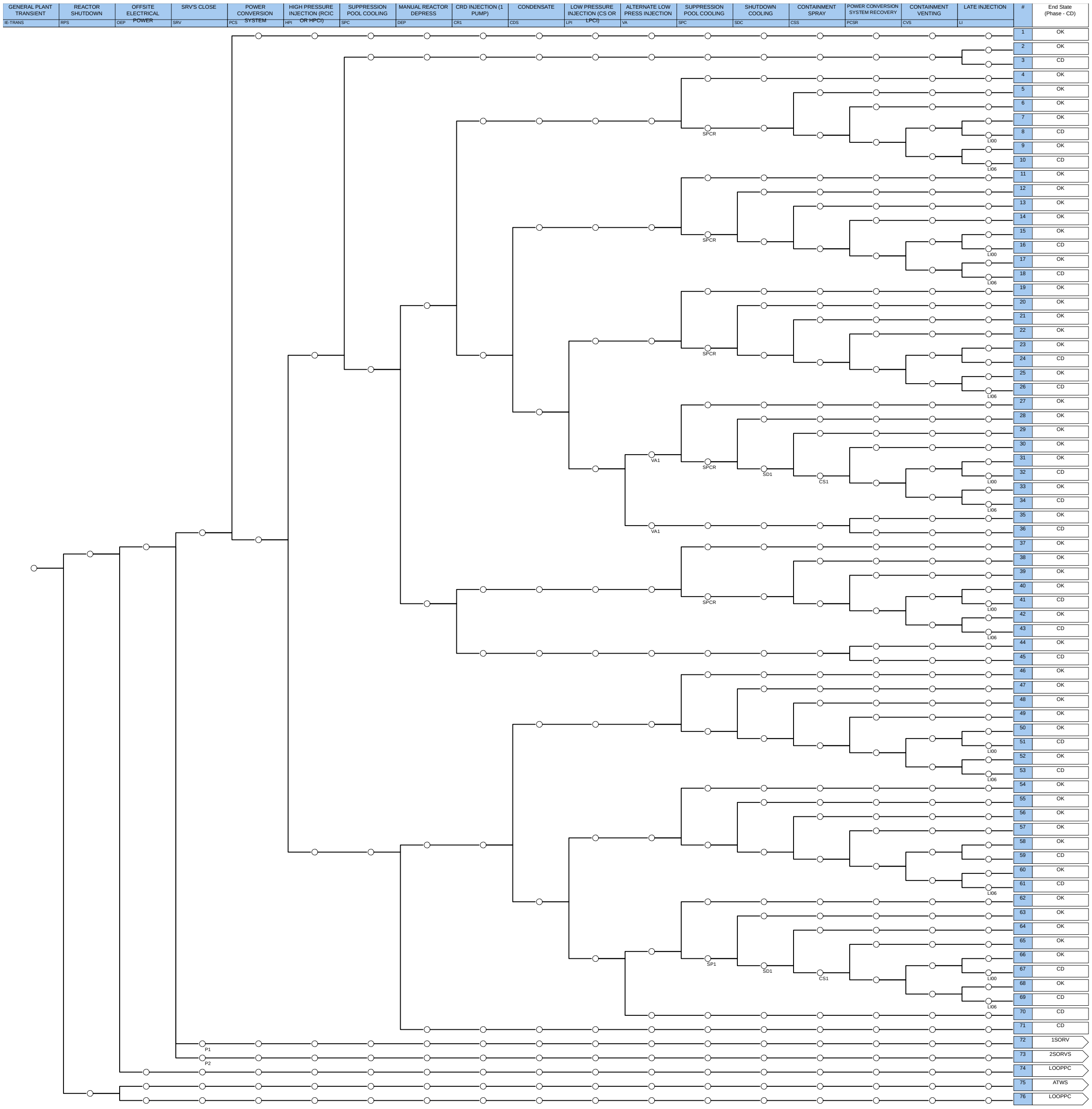


Figure 7-21. General Transient ET (IE-TRANS).

As with the PWR plant, the presence of the hydrogen facility near the BWR plant may cause a hydrogen leakage that leads to an explosion. This event may create a blast pressure that damages the switchyard components. If that happens, a switchyard-centered LOOP event will occur. The mitigation procedure due to a switchyard-centered LOOP IE is shown in Figure 7-22. Upon a LOOP event, the reactor is shut down and emergency power is activated. If safety relief valves remain closed while the HPI system and suppression pool cooling actuate, the reactor will be in a safe shutdown state. The tree logic is quite similar to the general transient tree. Redundant safety measures are incorporated in the tree, including manual depressurization followed by an LPI, an alternate LPI, shutdown cooling, containment spray, and containment venting to prevent an overpressure event.

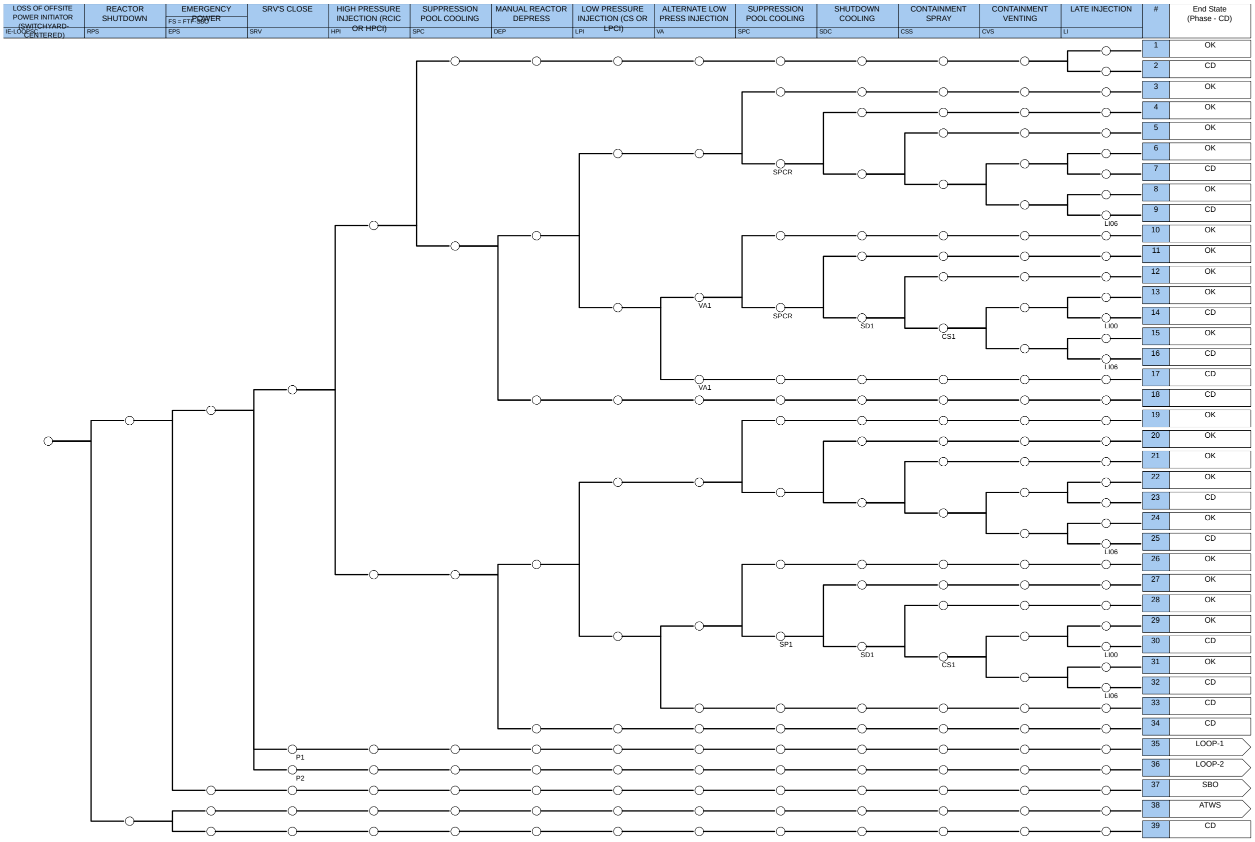


Figure 7-22. LOOP (Switchyard-centered) ET (LOOPSC).

7.3.1 Heat Extraction System Linkage into the Boiling Water Reactor Model

The mitigation procedure for a steam line break in the HES is shown in Figure 7-23. When the event occurs, the core will be damaged if the RPS fails or if the MSIVs fail to close. If both systems function properly, the mitigation tree transfers to the General Transient event tree as shown in Figure 7-21. However, since the General Transient tree is used as is, there needs to be a set of linkage rules to customize the tree based on the initiator (i.e., a steam line break in the HES). These linkage rules are set as pictured in Figure 7-24. It instructs SAPHIRE to activate the LSSB-HES Flag Set when the initiator is IE-LSSB-HES. This instruction is also carried over to the transfer ETs, i.e. General Transient. The LSSB-HES Flag Set is set up as shown in Figure 7-25. It activates the HE-SLB-TOT House event and changes its state from False to True. The same logic is used for other HES designs.

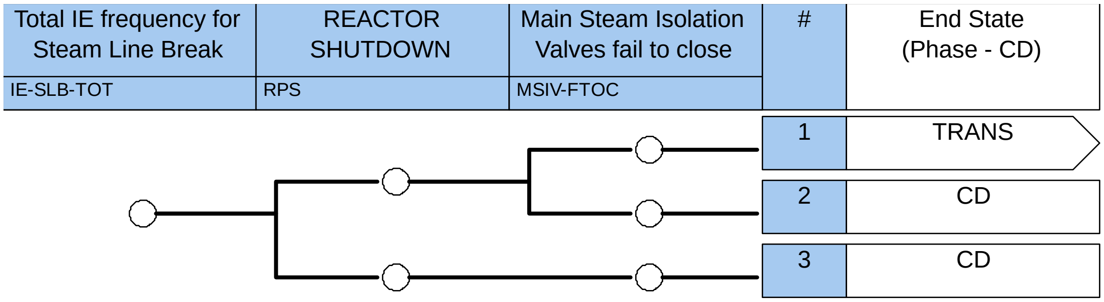
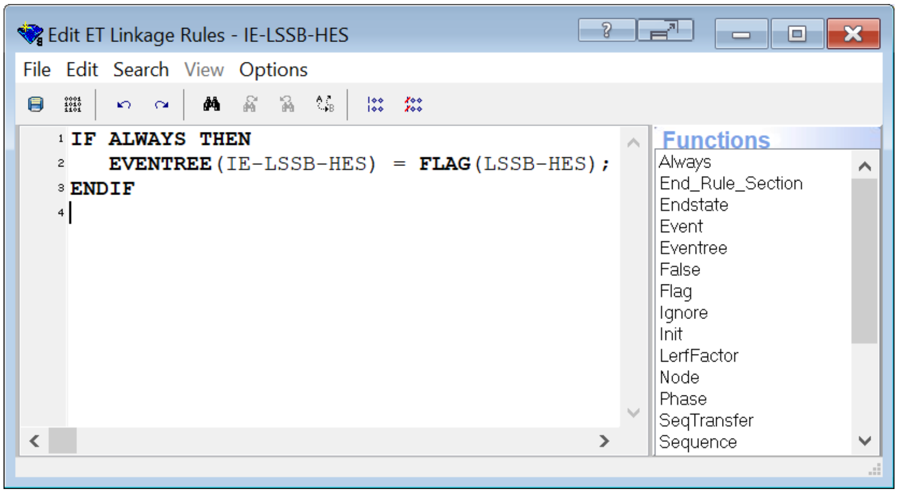
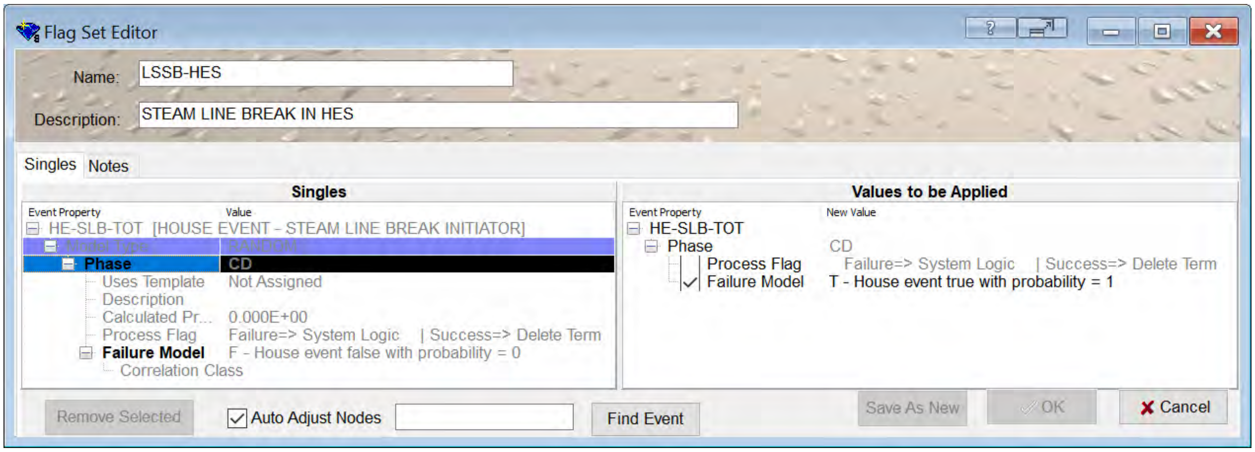


Figure 7-23. Initiating event for steam line break in the HES (IE-SLB-TOT).



```
IF ALWAYS THEN
   EVENTREE(IE-LSSB-HES) = FLAG(LSSB-HES);
ENDIF
```

Figure 7-24. Linkage rules for the IE-LSSB-HES ET



Name: LSSB-HES

Description: STEAM LINE BREAK IN HES

Singles

Event Property	Value
HE-SLB-TOT [HOUSE EVENT - STEAM LINE BREAK INITIATOR]	
Model Type	RANDOM
Phase	CD
Uses Template	Not Assigned
Description	
Calculated Pr...	0.000E+00
Process Flag	Failure=> System Logic | Success=> Delete Term
Failure Model	F - House event false with probability = 0
Correlation Class	

Values to be Applied

Event Property	New Value
HE-SLB-TOT	
Phase	CD
Process Flag	Failure=> System Logic | Success=> Delete Term
✓ Failure Model	T - House event true with probability = 1

☑ Auto Adjust Nodes

Figure 7-25. LSSB-HES flag editor.

As indicated in Figure 7-21, the IE-SLB-TOT ET transitions to the TRANS tree only when RPS functions successfully. For that reason, the RPS top event in the TRANS tree should not be evaluated again when the sequence originates from IE-SLB-TOT FT that determines the steam line break IE frequency. This logic is made possible by adding a complement of HE-SLB-TOT as shown in the RPS FT (Figure 7-26). This event is coupled in an AND gate with the other events that may cause RPS to fail. With this configuration, when the IE-SLB-TOT ET transitions to the TRANS tree, the LSSB-HES Flag is activated, and the HE-SLB-TOT House Event is set to true. Therefore, its complement becomes false, and the RPS failure top event does not occur. Meanwhile, when the TRANS tree is activated after the MSIV is closed, the Power Conversion System (PCS) is always off. This logic is implemented by adding the HE-SLB-TOT house event in an OR gate to the PCS and PCS recovery FT, as shown in Figure 7-27 and Figure 7-28 respectively.

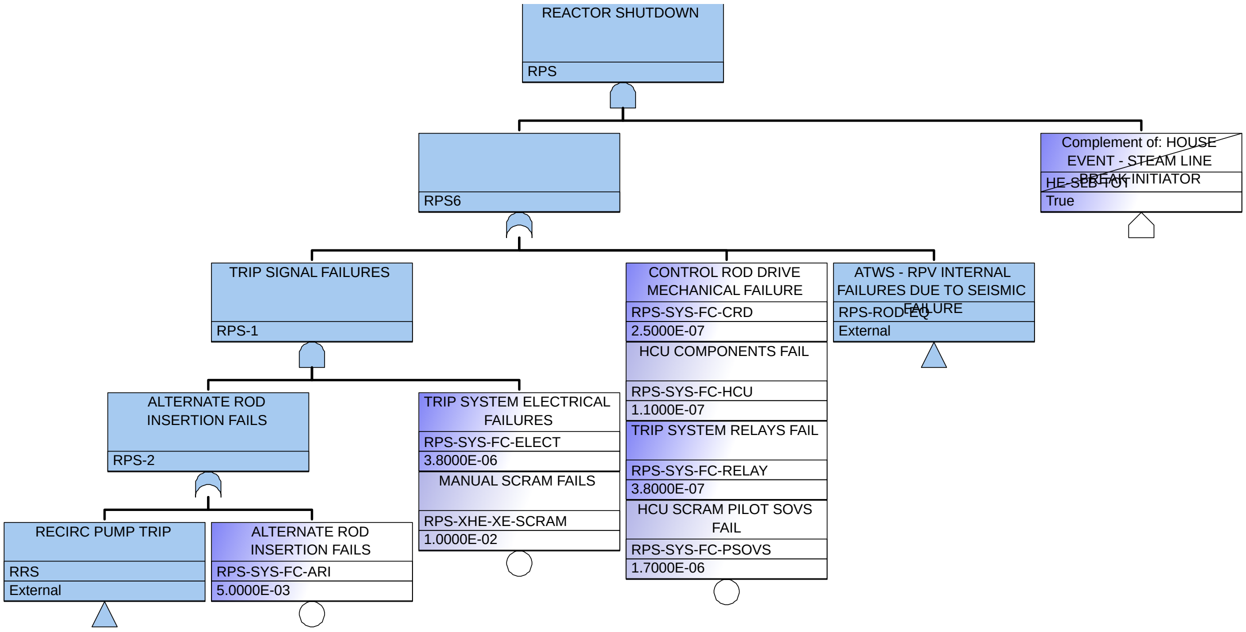


Figure 7-26. RPS FT.

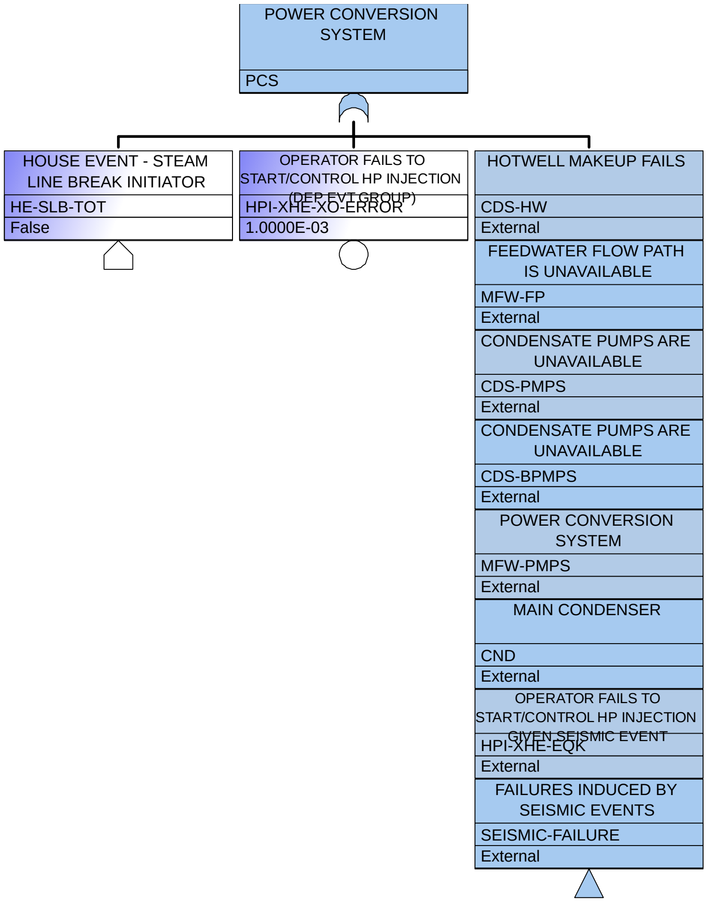


Figure 7-27. PCS FT.

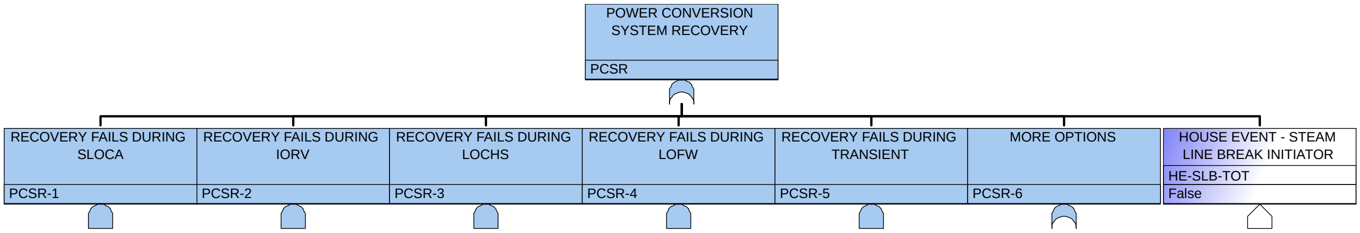


Figure 7-28. PCSR FT.

8. RESULTS OF PROBABILISTIC RISK ASSESSMENT

8.1 Nominal Probabilistic Risk Assessment Results

The required modifications listed in this report to support an HTEF affect the DBA IE frequencies and the CDF contribution of Main Steam Line Break, switchyard-related LOOP, and general transient. The results of the deterministic hazards analyses that set design assumptions for the PRA are provided throughout Section 6 by topic. The PRA results for PWR and BWR reactors are provided below.

8.1.1 Pressurized water reactor probabilistic risk assessment results

This section reports the IE frequencies and CDF for the nominal generic PWR model and the increases resulting from the addition of the 100, 500, and 1000 MW_{nom} HTEFs and the electrical connection to the HTEFs.

The overall PWR CDF increased minimally across the three HTEF HES designs (Table 8-1). The significance of the overall CDF increase is for RG 1.174 licensing support, if desired.

Table 8-1. Overall PWR core damage frequency results by HES modification

PWR Modification State	Overall CDF	% increase
Nominal	6.54E-06	nom
100 MW HES	6.55E-06	0.15%
500 MW HES	6.56E-06	0.31%
1000 MW HES	6.55E-06	0.15%

The HES design is the driver in the IE and CDF results for the steam line break DBA (Table 8-2). The most significant component in the HES designs are the motor operated isolation valves. The rupture failure of the isolation valves would require the NPP to shut down and the MSIVs to close to prevent loss of primary coolant, regardless of where the steam is tapped. The frequency of rupture of this motor operated valve is 1.2E-05 /y. The reboiler rupture failure is logically ANDed with the failure of the isolation valves to close, so the unisolated failure probability for the reboiler ruptures is 8.3E-10. This is five orders of magnitude below the isolation valve rupture which is why the 1000 MW_{nom} HTEF HES design, with three reboilers, has the same overall IE and CDF as the 100 MW_{nom} HTEF HES design with only one reboiler. The 500 MW_{nom} HTEF HES design shows the higher increase in IE and CDF because of the two isolation valves for the two steam taps.

Table 8-2. PWR Steam line break results by HES modification

PWR Modification State	Steam Line Break IE Frequency	% Increase	Steam Line Break CDF	% Increase
Nominal	3.01E-04	nom	2.51E-07	nom
100 MW HES	3.13E-04	3.85%	2.60E-07	3.83%
500 MW HES	3.24E-04	7.69%	2.70E-07	7.70%
1000 MW HES	3.13E-04	3.86%	2.604E-07	3.83%

The possibility of a detonation of hydrogen at the HTEF first affects the IE frequency of a switchyard-centered LOOP. The deterministic bounding analysis performed by SNL [14] and detailed in Section 6.1.5 effectively screens out the most common hydrogen detonation scenario, the hydrogen leak jet detonation as long as the safe siting distance is maintained and the HTEF outlet CPH is properly shielded through engineered barriers. The cloud detonation is considered in the PRA and its IE frequency increase for the largest 1000 MWnom HTEF is 3.49E-8, six orders of magnitude lower than the switchyard LOOP IE frequency.

Table 8-3. PWR Switchyard centered LOOP results by HES modification

PWR Modification State	Switchyard LOOP IE Frequency	% Increase	Switchyard LOOP CDF	% Increase
Nominal	1.34E-02	nom	2.69E-07	nom
100 MW HES	1.34E-02	0.00%	2.69E-07	0.000000260%
500 MW HES	1.34E-02	0.00%	2.69E-07	0.00000130%
1000 MW HES	1.34E-02	0.00%	2.69E-07	0.00000260%

The event that can increase the Transient IE is the overcurrent failure of the electrical connection between the NPP generator and the HTEF. The increase in the Transient IE is 9.16E-6, five orders of magnitude below the nominal Transient IE and is the same for each HTEF.

Table 8-4. PWR Transient results by HES modification

PWR Modification State	Transient IE Frequency	% Increase	Transient CDF	% Increase
Nominal	6.76E-01	nom	2.01E-07	nom
100 MW HES	6.76E-01	0.00%	2.01E-07	0.0000136%
500 MW HES	6.76E-01	0.00%	2.01E-07	0.0000136%
1000 MW HES	6.76E-01	0.00%	2.01E-07	0.0000136%

Seismic analysis results are from the increased failure probabilities of the components involved and obviously do not affect the IE frequencies of the seismic events. The summation of all seismic bins for the PRA model by HES modification show that the electrical seismic event additions do not increase the seismic CDF significantly as shown in Table 8-5.

Table 8-5. PWR Overall seismic results by HES modification

PWR Modification State	Seismic CDF	% Increase
Nominal	3.56E-06	nom
100 MW HES	3.56E-06	0.00122%
500 MW HES	3.56E-06	0.00122%
1000 MW HES	3.56E-06	0.00122%

8.1.2 Boiling water reactor probabilistic risk assessment results

This section reports the IE frequencies and CDF for the nominal generic BWR model and the increases resulting from the addition of the 100, 500, and 1000 MW_{nom} HTEFs and the electrical connection to the HTEFs.

The overall BWR CDF increased minimally across the three HTEF HES designs (Table 8-1). The significance of the overall CDF increase is for RG 1.174 licensing support, if desired. The very low changes in BWR CDF are due to the higher starting point of the nominal CDF and the same probabilistic results of the HES additions.

Table 8-6. Overall BWR core damage frequency results by HES modification

BWR Modification State	Overall CDF	% increase
Nominal	2.55E-05	nom
100 MW HES	2.55E-05	0.00016%
500 MW HES	2.55E-05	0.00018%
1000 MW HES	2.55E-05	0.00016%

The HES design is the driver in the IE and CDF results for the steam line break DBA (Table 8-8). The most significant component in the HES designs are the motor operated isolation valves. The rupture failure of the isolation valves would require the NPP to shut down and the MSIVs to close to prevent loss of primary coolant, regardless of where the steam is tapped. The frequency of rupture of this motor operated valve is 1.2E-05 /y. The reboiler rupture failure is logically ANDed with the failure of the isolation valves to close, so the unisolated failure probability for the reboiler ruptures is 8.3E-10. This is five orders of magnitude below the isolation valve rupture which is why the 1000 MW_{nom} HTEF HES design, with three reboilers, has the same overall IE and CDF as the 100 MW_{nom} HTEF HES design with only one reboiler. The 500 MW_{nom} HTEF HES design shows the higher increase in IE and CDF because of the two isolation valves for the two steam taps.

Table 8-7. BWR Steam line break results by HES modification

BWR Modification State	Steam Line Break IE Frequency	% Increase	Steam Line Break CDF	% Increase
Nominal	2.53E-03	nom	1.23E-07	nom
100 MW HES	2.54E-03	0.47%	1.24E-07	0.49%

BWR Modification State	Steam Line Break IE Frequency	% Increase	Steam Line Break CDF	% Increase
500 MW HES	2.55E-03	0.91%	1.24E-07	0.89%
1000 MW HES	2.54E-03	0.47%	1.24E-07	0.49%

The possibility of a detonation of hydrogen at the HTEF first affects the IE frequency of a switchyard-centered LOOP. The deterministic bounding analysis performed by SNL [14] and detailed in Section 6.1.5 effectively screens out the most common hydrogen detonation scenario, the hydrogen leak jet detonation as long as the safe siting distance is maintained and the HTEF outlet CPH is properly shielded through engineered barriers. The cloud detonation is considered in the PRA and its IE frequency increase for the largest 1000 MWnom HTEF is 3.49E-8, six orders of magnitude lower than the switchyard LOOP IE frequency.

Table 8-8. BWR Switchyard centered LOOP results by HES modification

BWR Modification State	Switchyard LOOP IE Frequency	% Increase	Switchyard LOOP CDF	% Increase
Nominal	1.34E-02	nom	6.55E-07	nom
100 MW HES	1.34E-02	0.00003%	6.55E-07	0.00%
500 MW HES	1.34E-02	0.00013%	6.55E-07	0.00%
1000 MW HES	1.34E-02	0.00026%	6.55E-07	0.00%

The event that can increase the Transient IE is the overcurrent failure of the electrical connection between the NPP generator and the HTEF. The increase in the Transient IE is 9.16E-6, five orders of magnitude below the nominal Transient IE and is the same for each HTEF.

Table 8-9. BWR Transient results by HES modification

BWR Modification State	Transient IE Frequency	% Increase	Transient CDF	% Increase
Nominal	7.40E-01	nom	3.78E-06	nom
100 MW HES	7.40E-01	0.00%	3.78E-06	0.00%
500 MW HES	7.40E-01	0.00%	3.78E-06	0.00%
1000 MW HES	7.40E-01	0.00%	3.78E-06	0.00%

Seismic analysis results are from the increased failure probabilities of the components involved and obviously do not affect the IE frequencies of the seismic events. The summation of all seismic bins for the PRA model by HES modification show that the electrical seismic event additions do not increase the seismic CDF significantly as shown in Table 8-10.

Table 8-10. PWR Overall seismic results by HES modification

BWR Modification State	Seismic CDF	% Increase
Nominal	3.56E-06	nom
100 MW HES	3.56E-06	0.00122%
500 MW HES	3.56E-06	0.00122%
1000 MW HES	3.56E-06	0.00122%

9. LICENSING PATHWAY SUPPORT FROM PROBABILISTIC RISK ASSESSMENT

The NRC uses codes of federal regulations and develops various regulatory guides to assist license applicants' implementation of NRC regulations by providing evaluation techniques and data used by the NRC staff. Two distinct pathways through guides and codes of federal regulations are used in the proposed LWR plant configuration change approval.

One pathway utilizes 10 CFR 50.59 [2] to review the effects of the proposed small changes to the NPP, including minimal increases in frequencies of DBAs, amend the updated final safety analysis report, and determine whether a licensing amendment review (LAR) is required. This pathway is dependent on the IE frequencies determination, which is on the front end of the PRA.

While the 10 CFR 50.59 evaluation does not specifically require a PRA, the PRA does provide numerical evidence of the effect of the proposed activities.

A supporting pathway utilizes RG 1.174 [3] using risk-informed metrics to approve a plant configuration change based on the effect on the overall CDF and LERF of an approved PRA. This pathway is dependent on the tail end of the analysis, the CDF and LERF resulting metrics of the PRA.

The final pathway is the LAR process, which would utilize PRA results as well; however, the process utilizes 10 CFR 50.90, "Application for amendment of license or construction permit at request of holder" [33] and is typically avoided if possible due to what is historically a more lengthy review and monetary burden.

9.1 Licensing Process through 10 CFR 50.59

This licensing pathway first uses 10 CFR 50.59 [2] to determine if an LAR would be required via 10 CFR 50.90 [33]. Changes that meet the 10 CFR 50.59 requirements do not require additional NRC review and approval. In a studies commissioned by LWRS [34][35] , the effects on DBAs of a PWR with the addition of an HES were evaluated for adherence to the following eight criteria:

1. Result in more than a minimal increase in the frequency of occurrence of an accident previously evaluated in the final safety analysis report (as updated)
2. Result in more than a minimal increase in the likelihood of occurrence of a malfunction of a structure, system, or component important to safety previously evaluated in the final safety analysis report (as updated)
3. Result in more than a minimal increase in the consequences of an accident previously evaluated in the final safety analysis report (as updated)

4. Result in more than a minimal increase in the consequences of a malfunction of an SSC important to safety previously evaluated in the final safety analysis report (as updated)
5. Create a possibility for an accident of a different type than any previously evaluated in the final safety analysis report (as updated)
6. Create a possibility for a malfunction of an SSC important to safety with a different result than any previously evaluated in the final safety analysis report (as updated)
7. Result in a design basis limit for a fission product barrier as described in the final safety analysis report (as updated) being exceeded or altered
8. Result in a departure from a method of evaluation described in the final safety analysis report (as updated) used in establishing the design bases or in the safety analyses.

If the above criteria are not met, the 10 CFR 50.59 process cannot be used to implement the plant modification and an LAR must be submitted to the NRC for review and approval.

The S&L study noted that all deterministic criteria are met for a 10 CFR 50.59 application based on the modifications noted in their report [35]. This report uses the same modifications as the S&L study for the HESs to support 100 and 500 MWnom HTEF designs. The HES for the 1000 MWnom HTEF is an extension design proposed by INL based on generalized recommendations from S&L and other LWR experts. As noted in References [34] and [35], nearly all criteria are readily met for a modification such as the HES, but there was not enough data available at the time to determine if item 1 (minimal increase in DBA frequency) is met probabilistically. A minimal increase is traditionally understood to be ≤10% as proposed by the Nuclear Energy Institute (NEI), "Guidelines for 10 CFR 50.59 Implementation," [36]. Specifically, Example 8 states:

> *The change in likelihood of occurrence of a malfunction is calculated in support of the evaluation and increases by more than a factor of two. Note: The factor of two should be applied at the component level. Certain changes that satisfy the factor of two limit on increasing likelihood of occurrence of malfunction may meet one of the other criteria for requiring prior NRC approval, e.g., exceed the minimal increase standard for accident/transient frequency under criterion 10 CFR 50.59(c)(2)(i). For example, a change that increases the likelihood of malfunction of an emergency diesel generator by a factor of two may cause more than a 10% increase in the frequency of station blackout.*

Reference [36] is endorsed by the NRC in "Guidance for Implementation of 10 CFR 50.59, Changes, Tests, and Experiments," Regulatory Guide (RG) 1.187 [37]. This PRA found the largest increase in a DBA yearly IE frequency to be 7.69% (Large Steam Line Break for the PWR) from all considered HES Designs, thus meeting the item 1 criteria for 10 CFR 50.59.

9.2 Licensing Support through RG 1.174

RG 1.174 [3] provides general guidance concerning analysis of the risk associated with proposed changes in plant design and operation. Specifically, thresholds and guidelines are provided for comparison with Level 1 PRA results for CDF and LERF.

As seen in Figure 9-1, CDF should be below ~1E-3/y overall and the change in overall CDF should be below a magnitude of 1E-5/y. Any plant that starts at a 1E-4 or more CDF requires less than 1E-6/y increase in CDF to be considered. Both the generic BWR and PWR nominal CDFs are below 1E-5/y. The largest increase in CDF of the two LWRs in this report is ΔCDF of 2.0E-8/y for the generic PWR with a 500 MWnom HES design. This result is well within these metrics; therefore, the NRC most likely considers this a small change consistent with the intent of the Commission's Safety Goal Policy Statement and a detailed quantitative assessment of the base values of CDF is not necessary for the license review.

If the above criteria for CDF were not met, an LAR must be submitted to the NRC for review and approval.

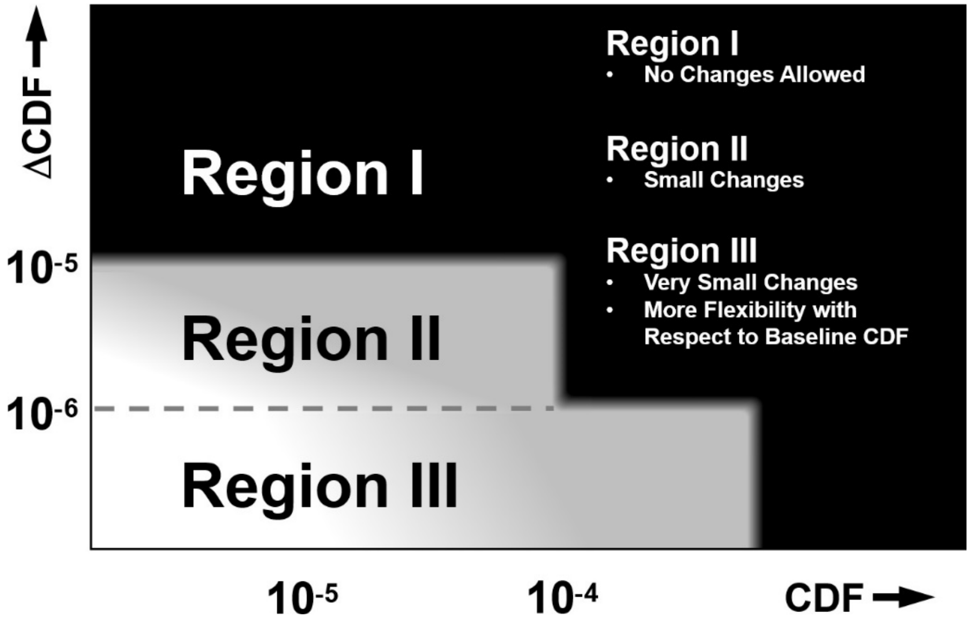


Figure 9-1. Acceptance guidelines for CDF.

As seen in Figure 9-2, LERF should be below ~1E-4 overall and the change in overall LERF should be below a magnitude of 1E-6. Both the generic BWR and PWR nominal LERFs are below 1E-6/y. The largest increase in LERF of the two LWRs in this report is a ΔLERF of 5.1E-7/y for the generic BWR with a 500 MWnom HES design. This result is well within these metrics; therefore, the NRC most likely considers this a small change consistent with the intent of the Commission's Safety Goal Policy Statement and a detailed quantitative assessment of the base values of CDF is not necessary for the license review. The LERF for these models is well within Region III.

If the above criteria for LERF were not met, an LAR must be submitted to the NRC for review and approval.

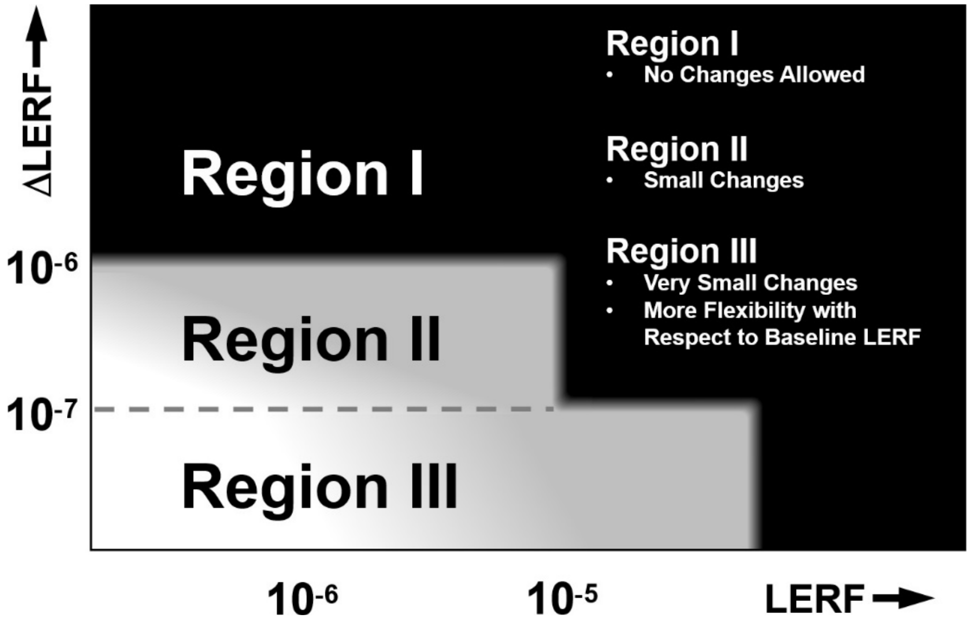


Figure 9-2. Acceptance guidelines for LERF.

9.3 Licensing Support Through RG 1.91

RG 1.91 [11] is the current NRC regulation guide for evaluating explosion risks near an NPP. Some NPPs have used RG 1.91 analyses in their safety case. The TNT methodology and standoff distances equivalent to a 1 psi overpressure are the absolute minimum safe distance requirements for RG 1.91.

The risk-informed approach of the Bauwens method along with SSC fragilities is a key contributor to safe siting distance to meet 10 CFR 50.59 minimal increase of DBA IEs. This report used switchyard components leading to a LOOP as to answer 10 CFR 50.59 question 1 in Section 9.1, however it doesn't appear to be the intent for RG 1.91 to include switchyard components as critical SSCs. The 1.0 psi limit of RG 1.91 is conservative when evaluating for the safety of the reactor walls (rated safe for 1.5 psi) and other safety structures such as coolant supply tanks, but not sufficient for switchyard components.

9.4 Licensing Amendment Review Process

Should the prior two processes fail to approve a change in the LWR, the last resort would be a detailed request for an LAR. As stated in Reference [34]:

> *10 CFR 50.90 is the governing regulation for the process undertaken by the licensee to develop and submit an LAR. This regulation states that the application fully describes the changes desired and is to follow the form prescribed for the original updated final safety analysis report submittal. An LAR is required when a change to the technical specifications is desired for whatever purpose. The LAR is developed by the licensee staff and is reviewed by internal committees and management to ensure that the technical content is correct and meets management approval.*

The NRC LAR review is extensive and typically involves meetings with the licensee and the opportunity for public meetings per 10 CFR 50.91, "Notice for Public Comment; State Consultation" [38]. The NRC issues requests for additional information to obtain responses from the licensee as a result of the NRC review. 19 CFR 50.92, "Issuance of Amendment" [39] includes a "no significant hazards" consideration to determine if any of the following conditions exist based on the NRC LAR review:

- Involves a significant increase in the probability or consequences of a previously evaluated accident
- Creates the possibility of a new of different kind of accident from any previously evaluated accident
- Involves a significant reduction in margin of safety.

Provided these regulatory requirements are met, the NRC issues, a safety evaluation that approves the LAR including the technical specification revisions.

10. CONCLUSIONS

Higher amounts of detail in the specifications of the generic HTEFs were used to produce safe standoff distances and probabilistic results for a 100, 500, and 1000 MW_{nom} HTEFs. The facility hazards and footprint were assessed to determine the safe distance required for placement near the nuclear power plant (NPP). Hazards and siting analyses of the specified HTEFs provided insights to placement of the HTEF not only for the NPP, but also for the community. Additional hazard assessments of 1000 kg of hydrogen storage and high wind effects on stacked SOECs were performed.

The deterministic analyses in this report define the safe separation distance between the point of detonation MCAs in the HTEF to the most fragile SSC in the NPP (switchyard transmission tower). These analyses confirmed the need for engineered barriers to protect the hydrogen CPH of the 500 and 1000 MW_{nom} HTEFs. Further analysis prescribes the need for engineered barrier protection of any hydrogen storage tank to eliminate the effects of a possible tank shear and detonation accident that was not quantifiable as of the publication of this report.

The PRAs include the deterministic and other hazards analyses driven design assumptions (Table 6-1) necessary to maintain safety at the separation distances prescribed in this report, both for the hydrogen detonation-specific Bauwens method used to find the safe overpressure distance from switchyard transmission towers (Table 6-8) and for the RG 1.91 calculations for TNT equivalent distance to 1.0 psi overpressure (Section 6.1.5). The HTEF designs used in this project were designed by S&L (100 and 500 MW_{nom}) or designed by INL based on S&L designs and general recommendations (1000 MW_{nom}).

The hazards analyses and PRA confirm with high confidence that by using the assumptions of design in this report (Table 6-1) the safety case for licensing an HES addition and an HTEF sited with its unprotected high-pressure stage components 187 meters from the NPP's transmission towers (the most fragile SSC) is strong. The results of the PRA indicate that the 10 CFR 50.59 licensing approach is justified due to the minimal increase in IE frequencies for all DBAs, with none exceeding 7.7% (Section 8). The PRA results for CDF and LERF support the use of RG 1.174 as further risk information that supports a change without a full LAR (Section 9.2).

This PRA investigation outlines a successful pathway to follow for deterministic and probabilistic analyses when moving to the site-specific case.

11. REFERENCES

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Appendix A: Generic PWR PRA Model

This Appendix shows PWR ETs, which are transfers of the accident mitigation ETs described in the body of this report.

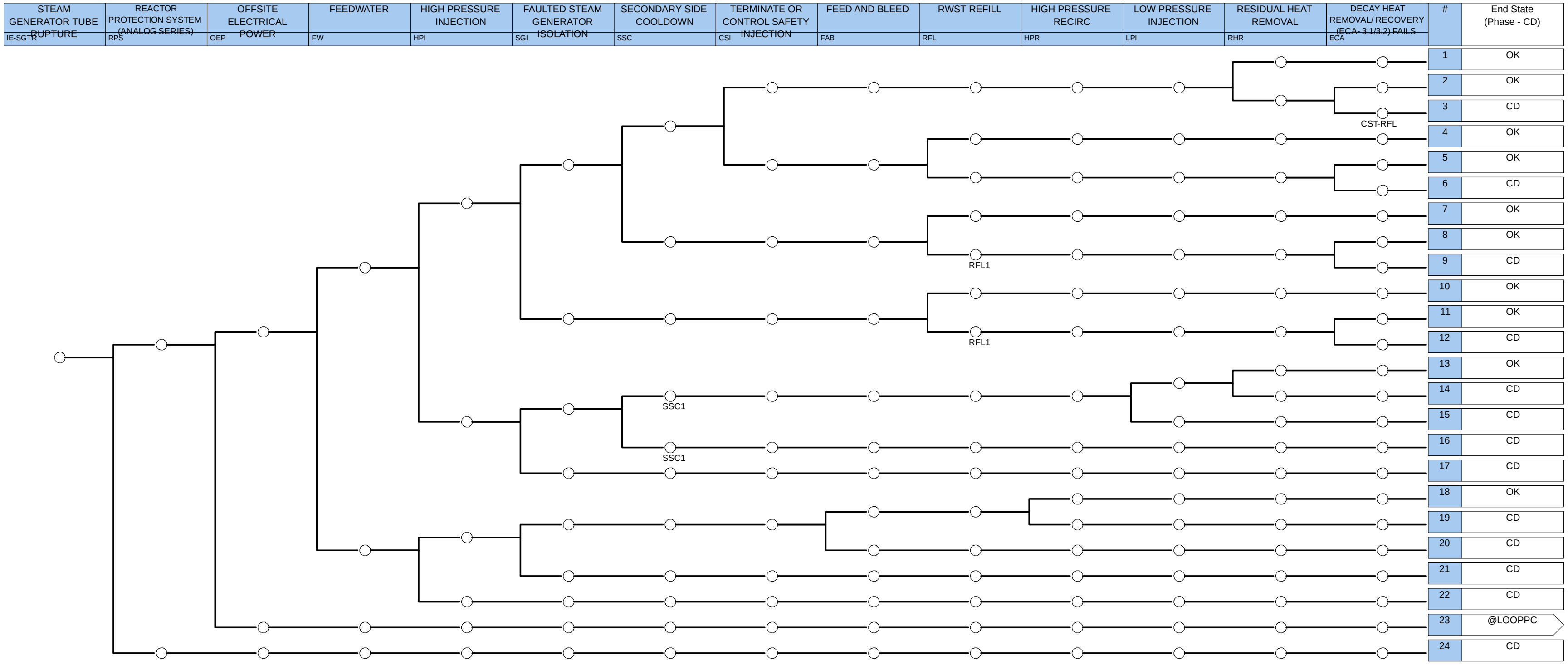


Figure A- 1. SGTR ET.

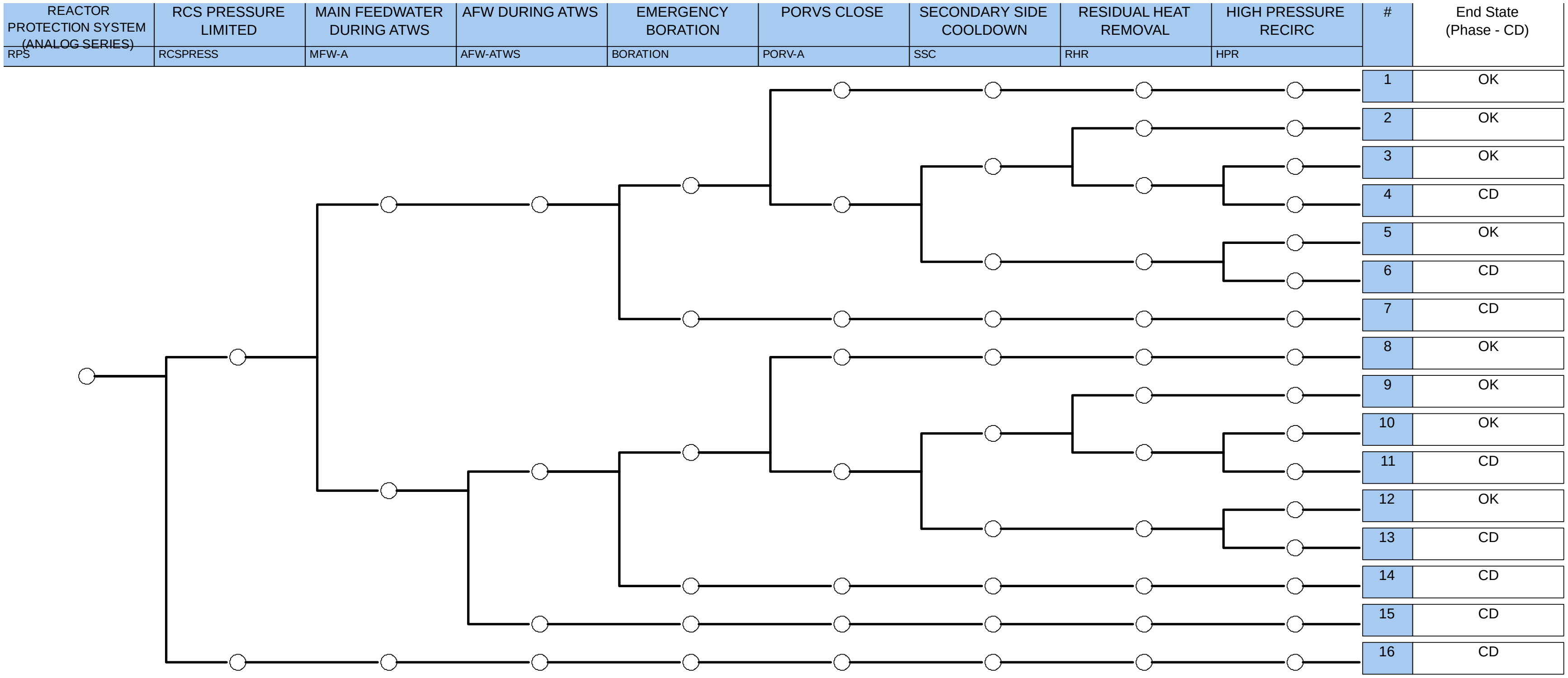
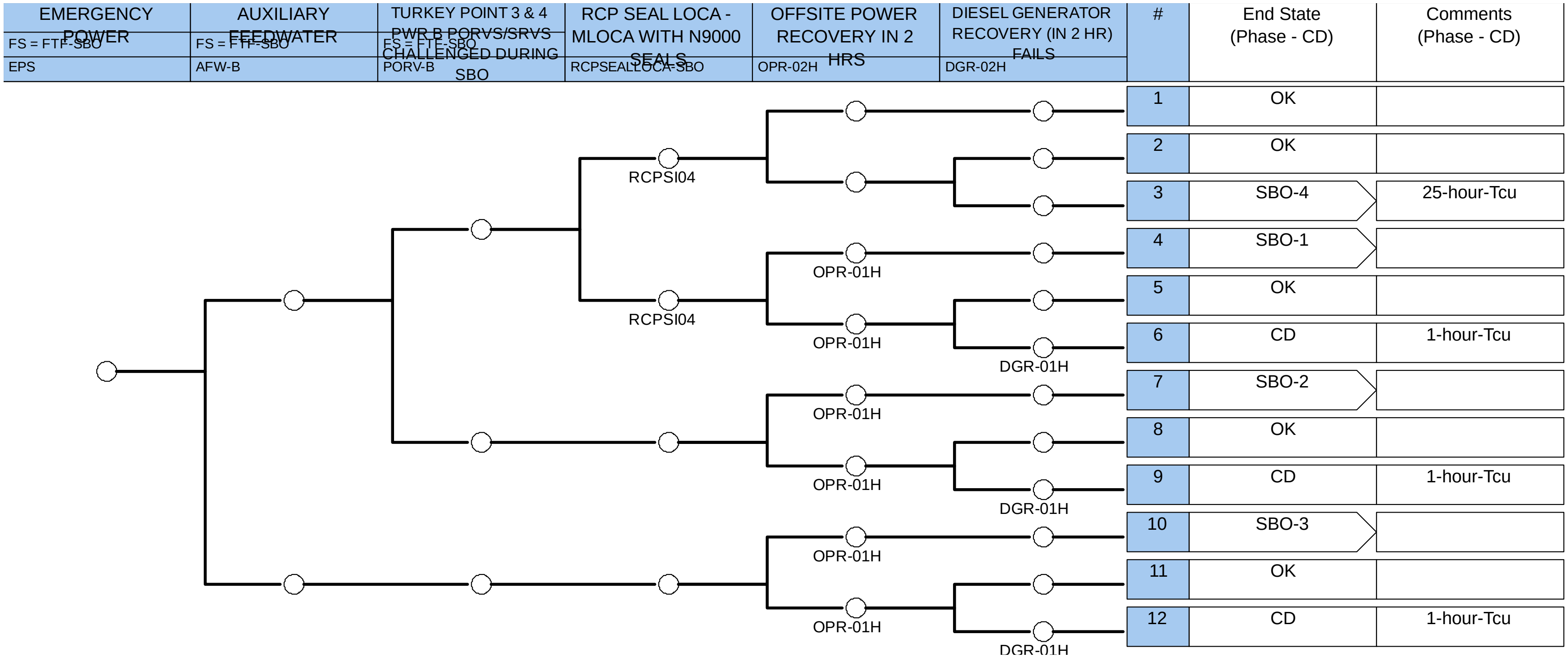


Figure A- 2. ATWS ET.



#	End State (Phase - CD)	Comments (Phase - CD)
1	OK	
2	OK	
3	SBO-4	25-hour-Tcu
4	SBO-1	
5	OK	
6	CD	1-hour-Tcu
7	SBO-2	
8	OK	
9	CD	1-hour-Tcu
10	SBO-3	
11	OK	
12	CD	1-hour-Tcu

Figure A- 3. Station blackout (SBO) ET.

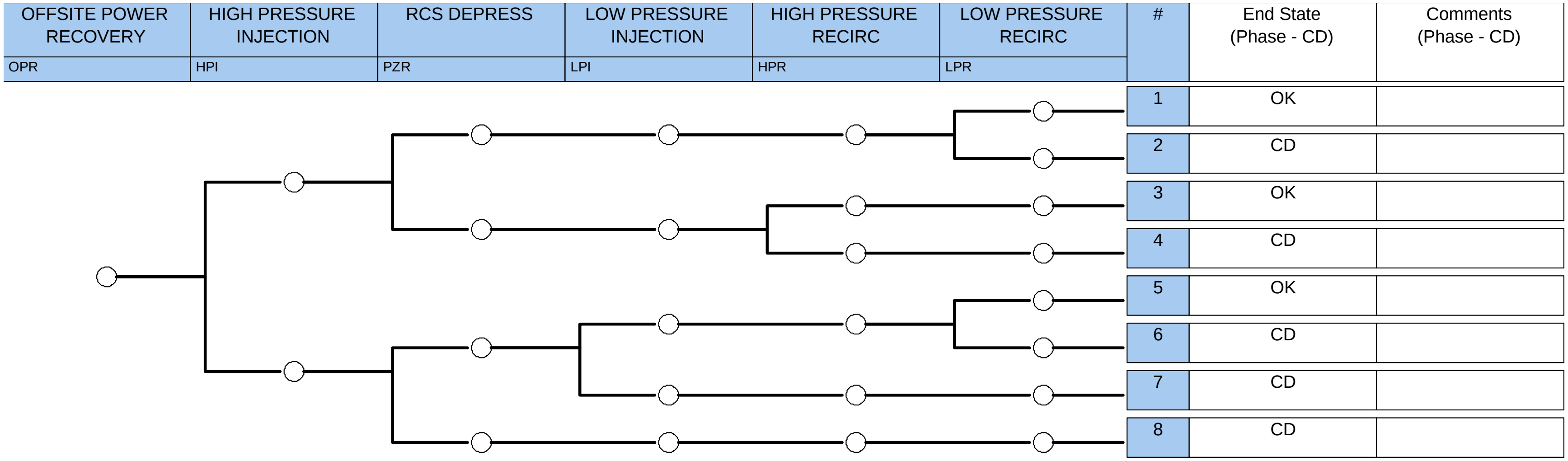


Figure A- 4. SBO-1 ET.

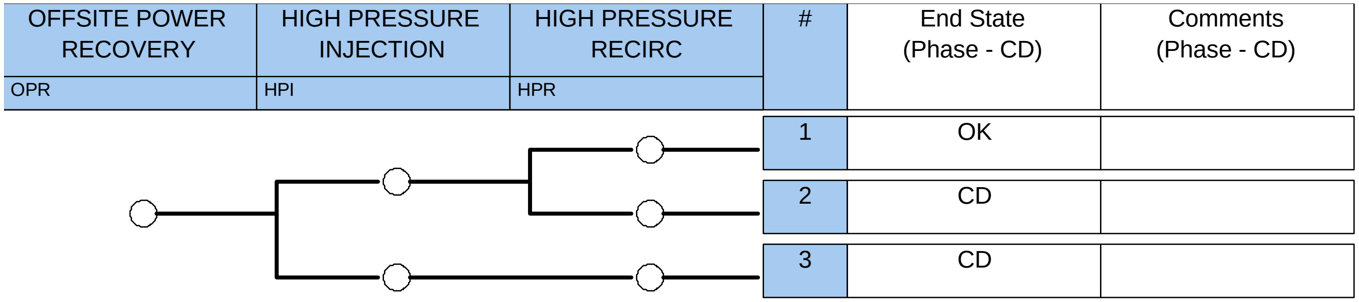


Figure A- 5. SBO-2 ET.

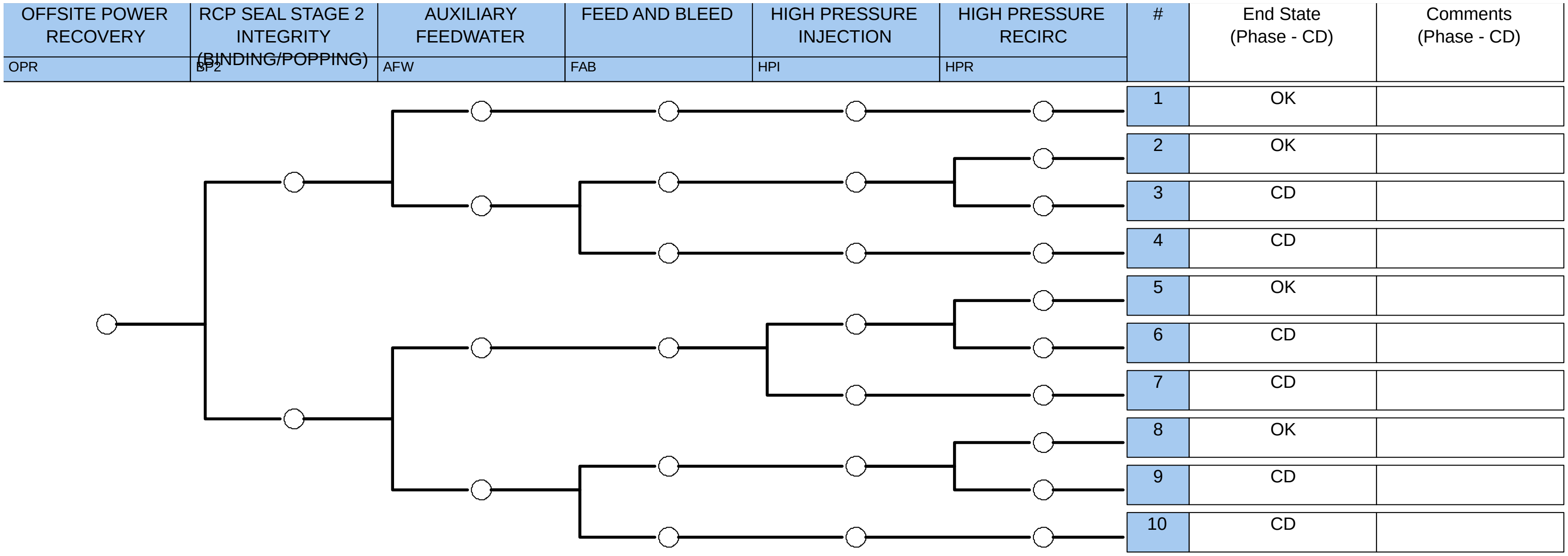


Figure A- 6. SBO-3 ET.

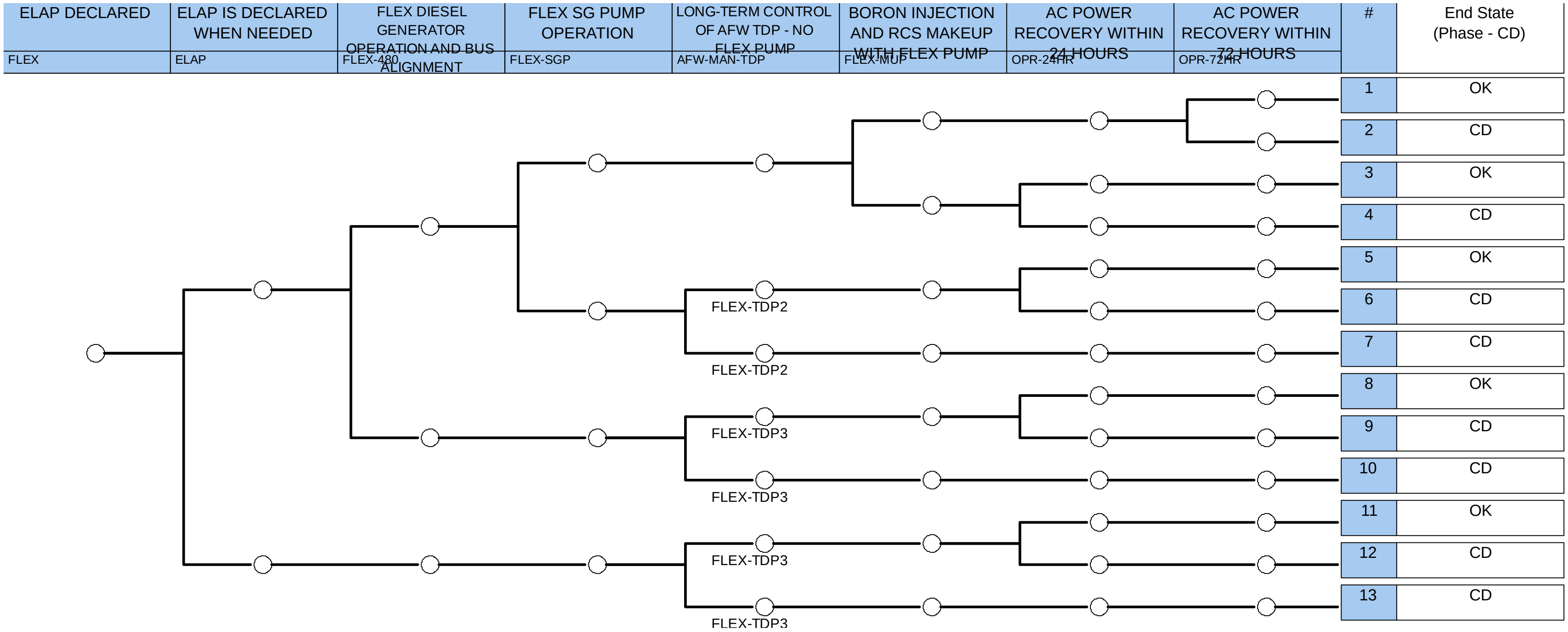


Figure A- 7. SBO-4 ET.

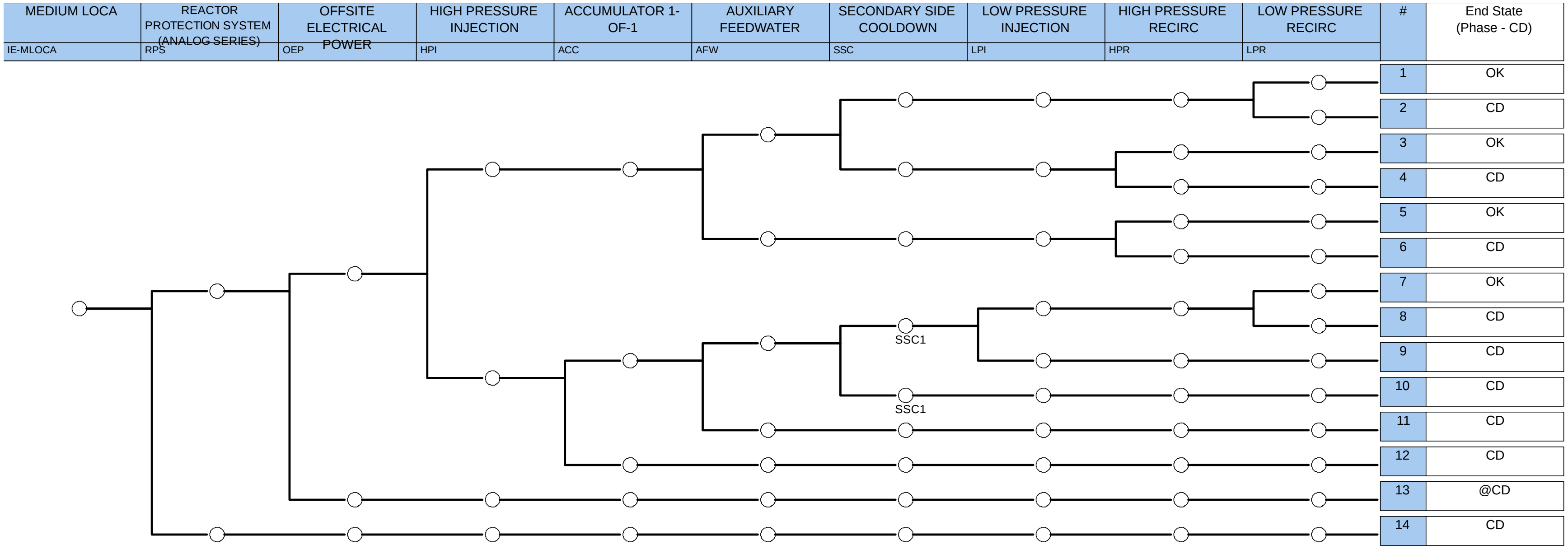


Figure A- 8. Medium loss-of-coolant accident ET.

Appendix B: Generic BWR PRA Model

This Appendix shows BWR ETs, which are transfers of the accident mitigation ETs described in the body of this report. The General plant transient ET previously shown in Section 7.3 is truncated and displayed in several parts here for better readability. The one stuck-open relief valve ET is shown in multiple parts for the same reason.

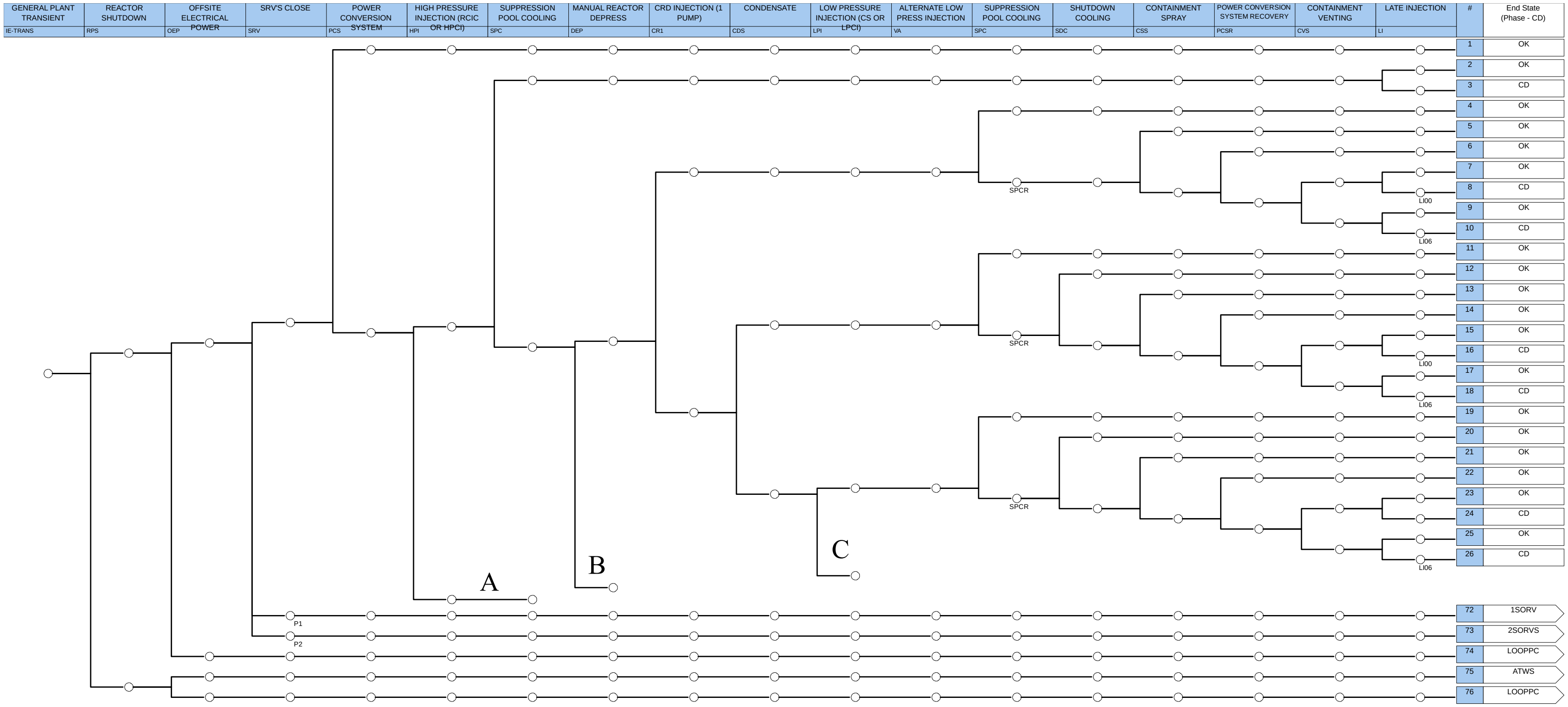


Figure B- 1. General plant transient ET (IE-TRANS) Part 1, showing three truncated branches (i.e., branch A, B, and C).

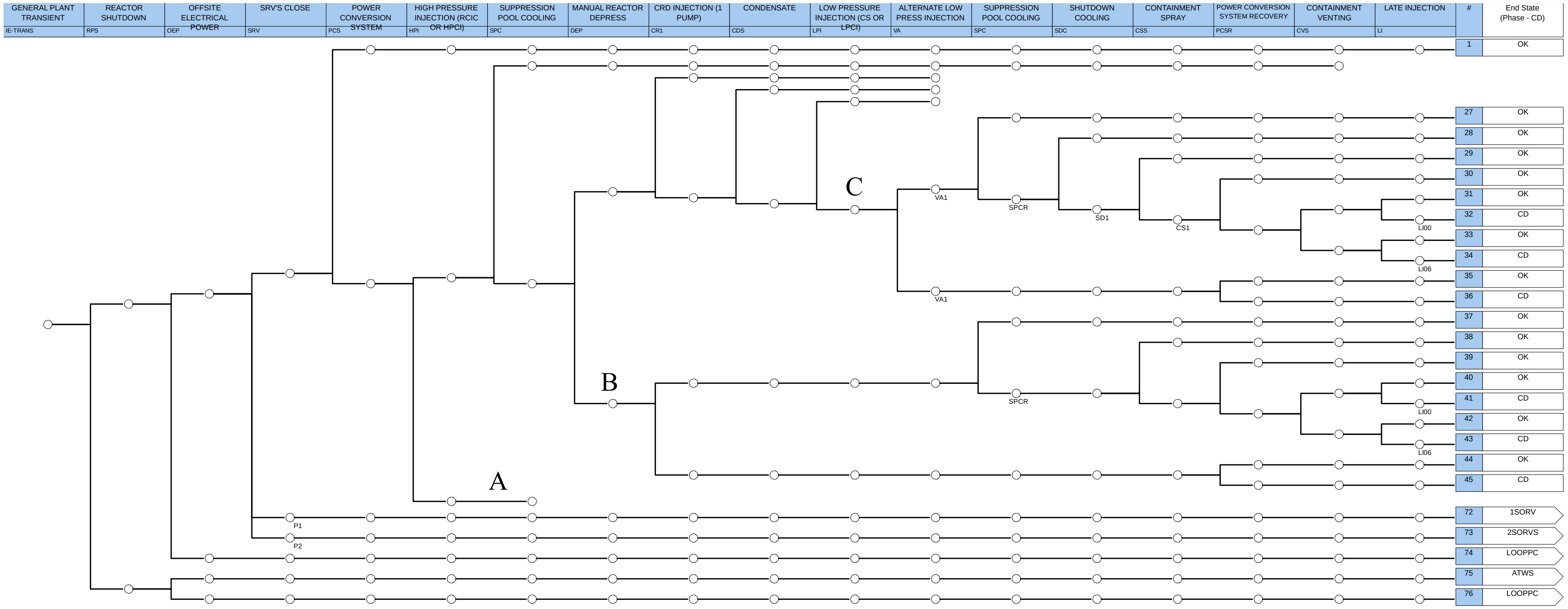


Figure B- 2. General plant transient ET (IE-TRANS) Part 2, revealing branch B and C.

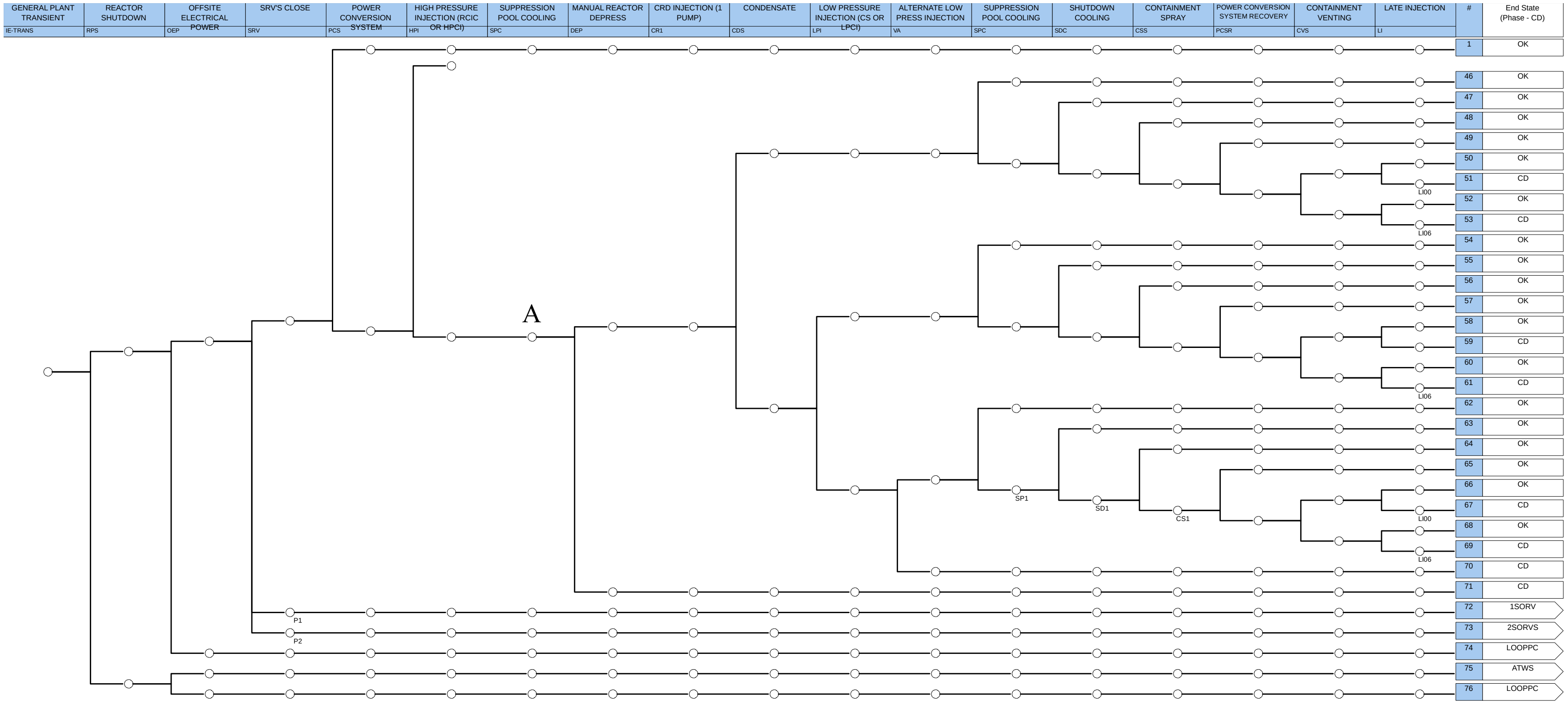


Figure B- 3. General plant transient ET (IE-TRANS) Part 3, revealing branch A.

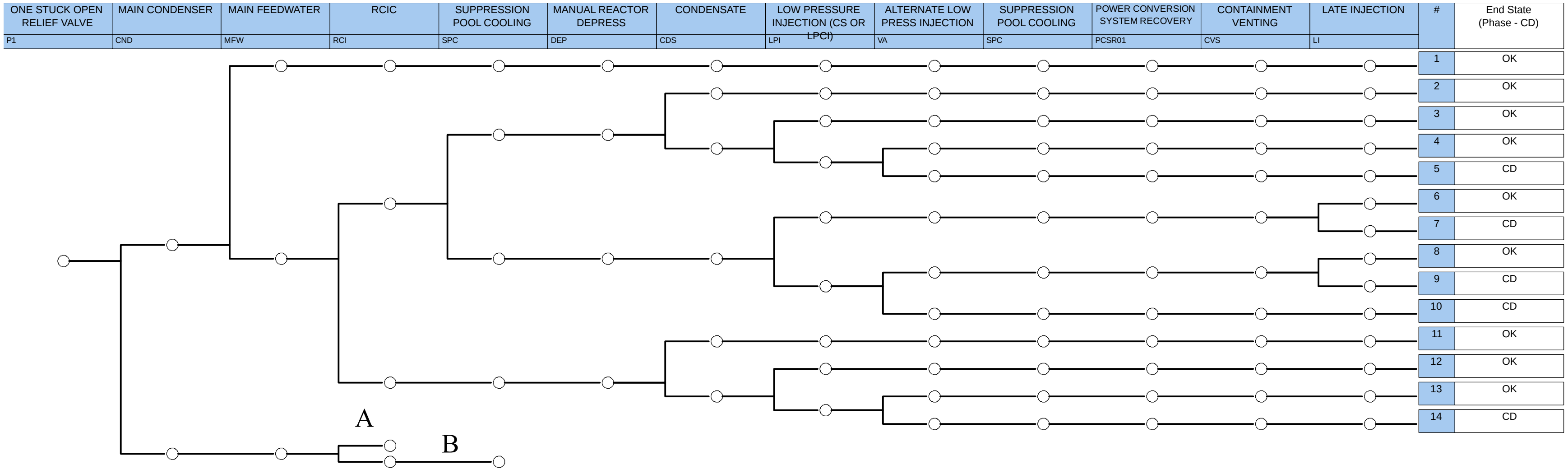


Figure B- 4. One stuck-open relief valve ET (P1) Part 1, showing a truncated branch.

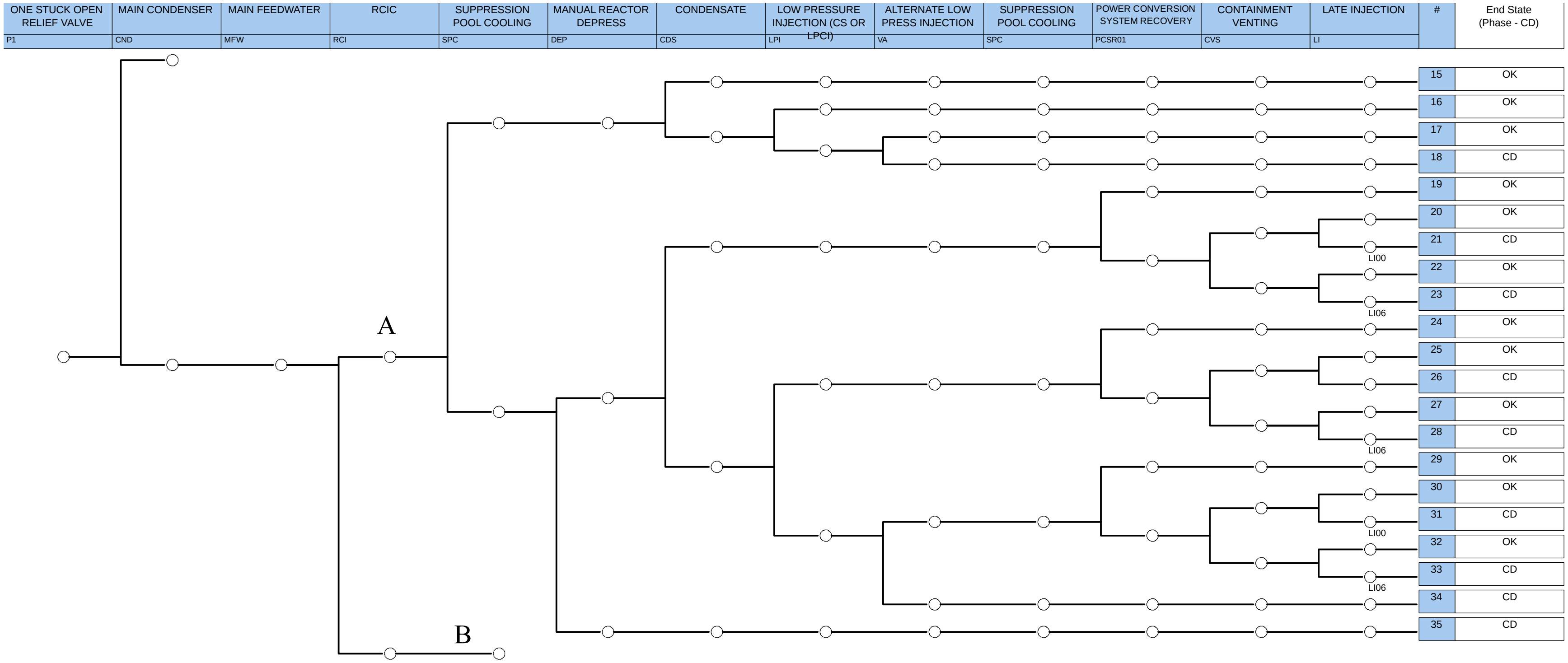


Figure B- 5. One stuck-open relief valve ET (P1) Part 2, revealing branch A.

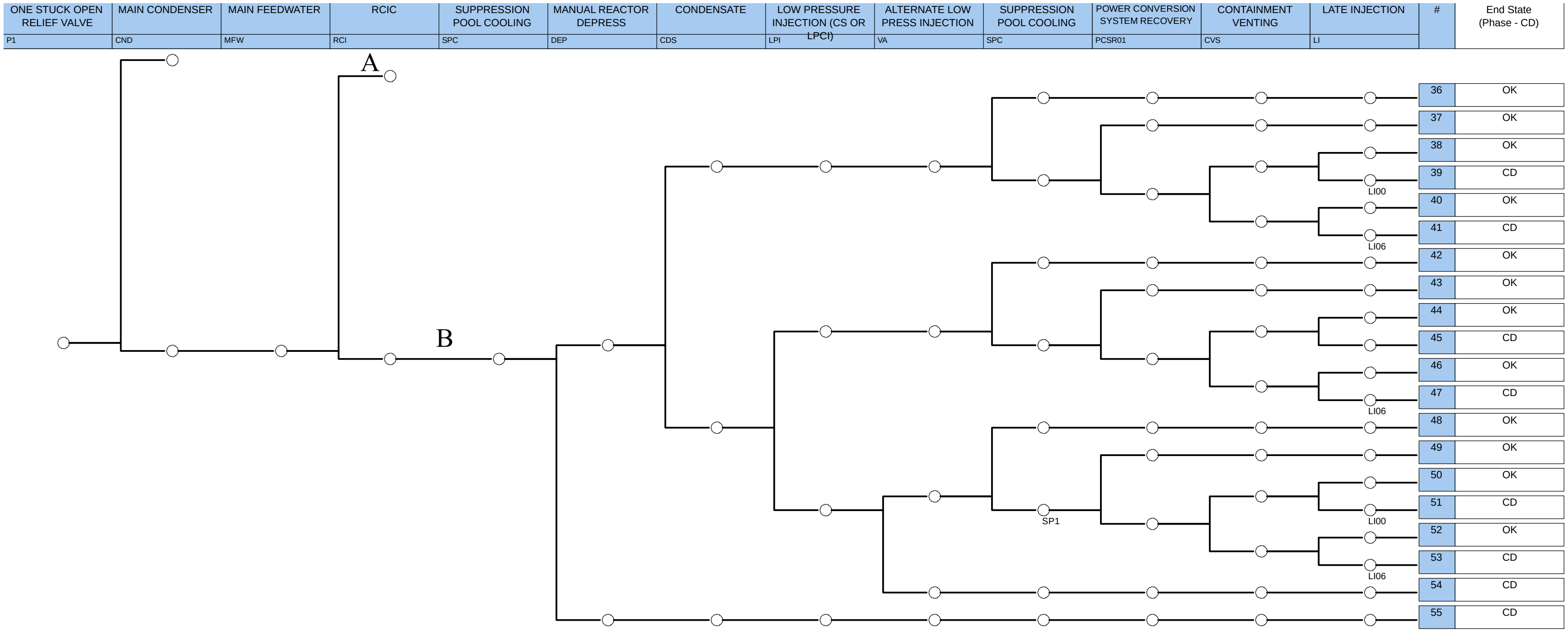


Figure B- 6. One stuck-open relief valve ET (P1) Part 3, revealing branch B.

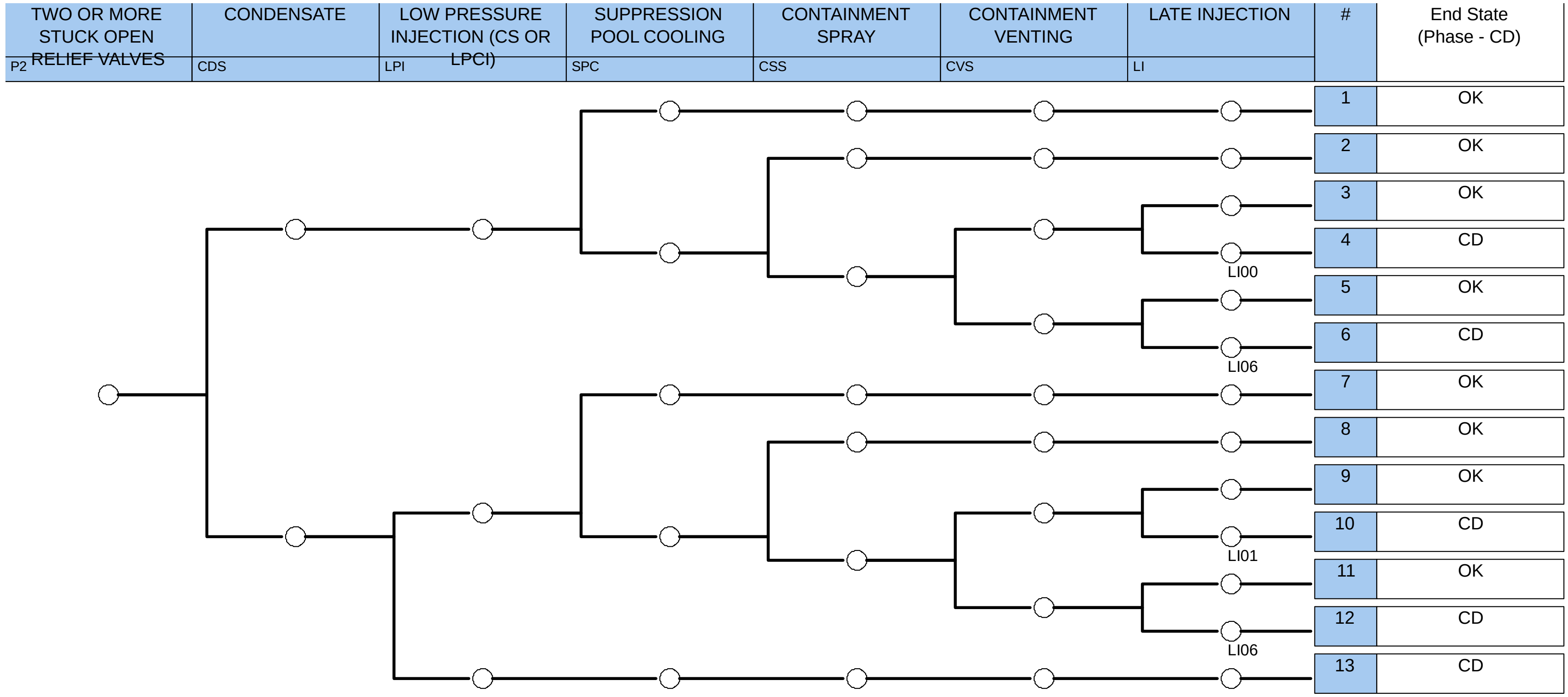


Figure B- 7. Two or more stuck-open relief valves (P2).

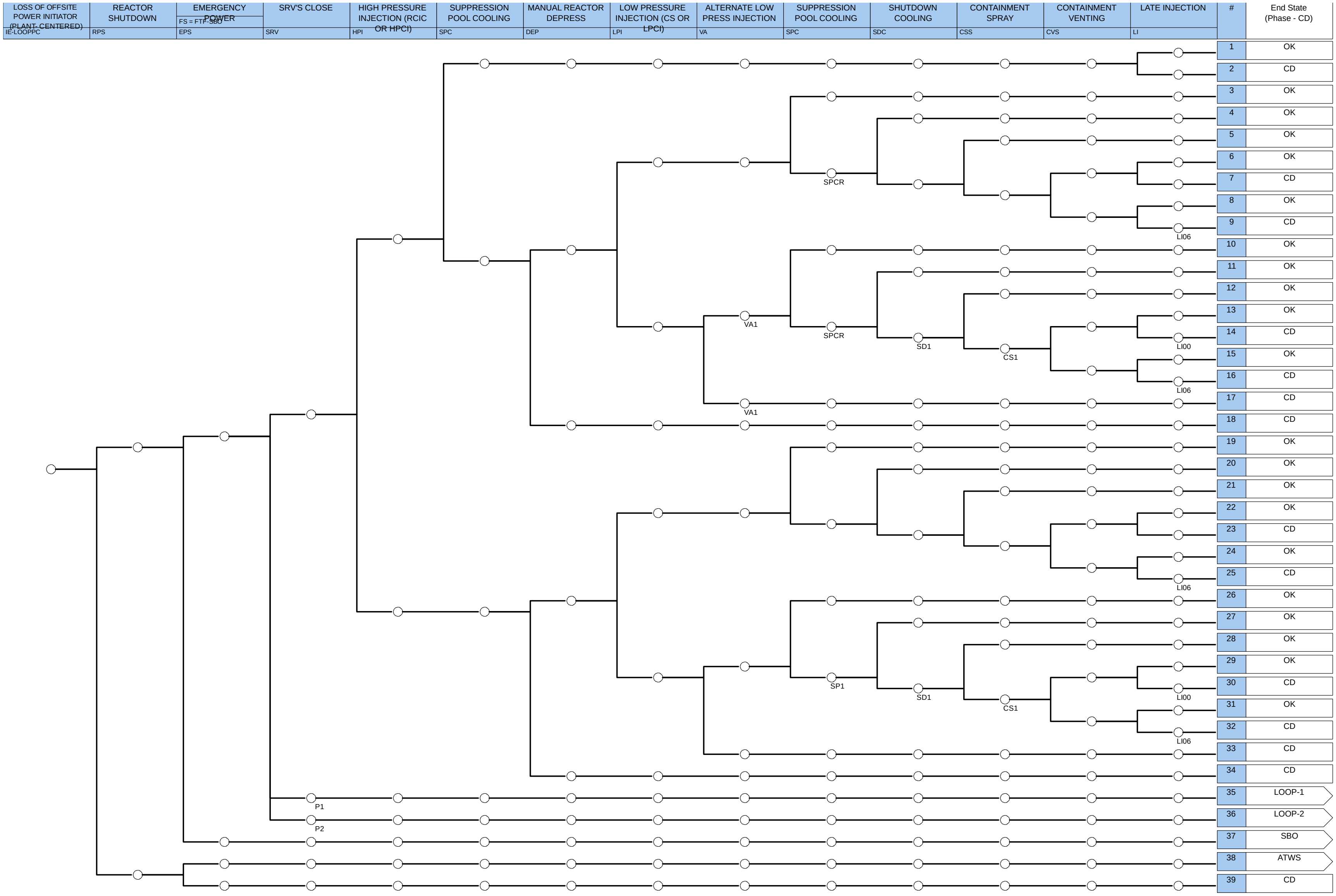


Figure B- 8. LOOP (plant-centered) ET (IE-LOOPPC).

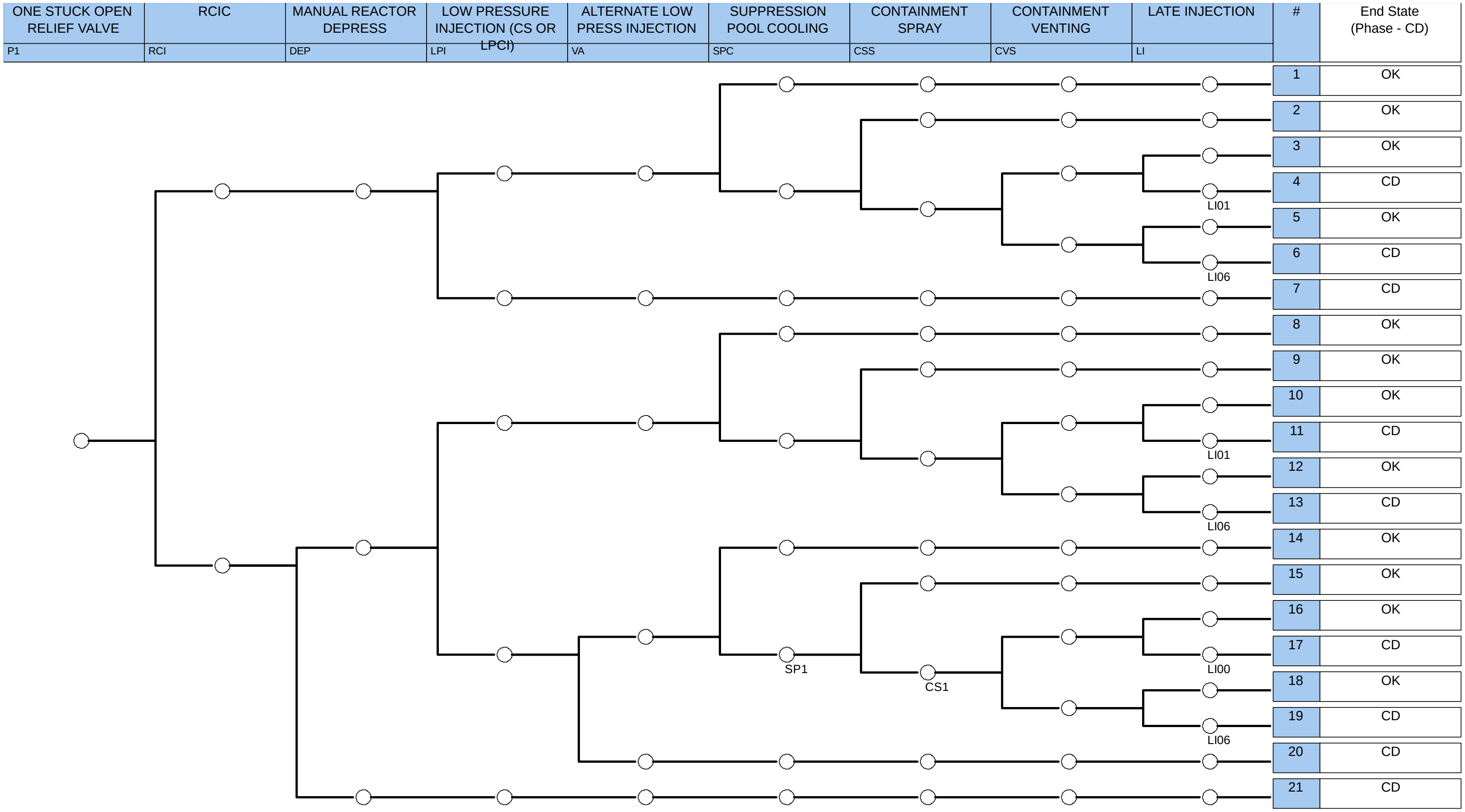


Figure B- 9. LOOP-1 ET (P1).

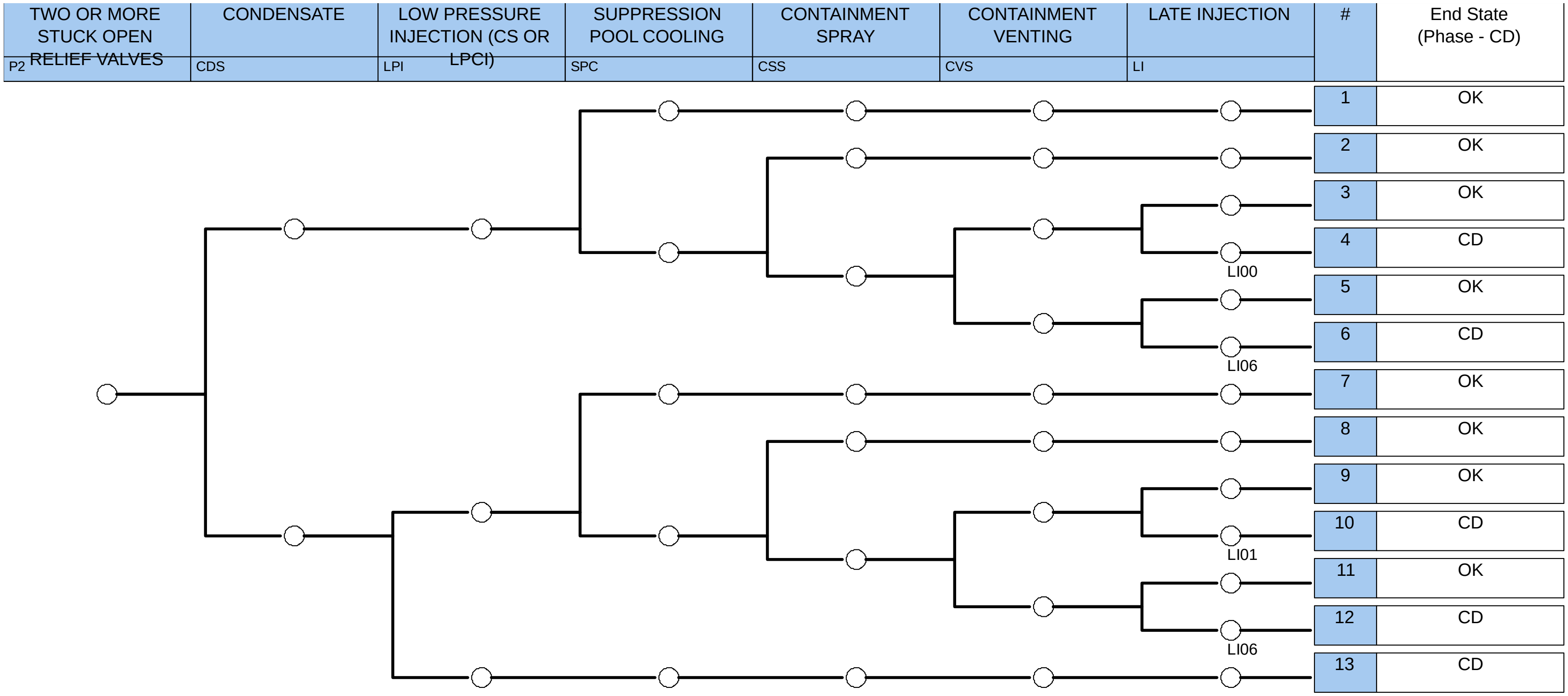


Figure B- 10. LOOP-2 ET (P2).

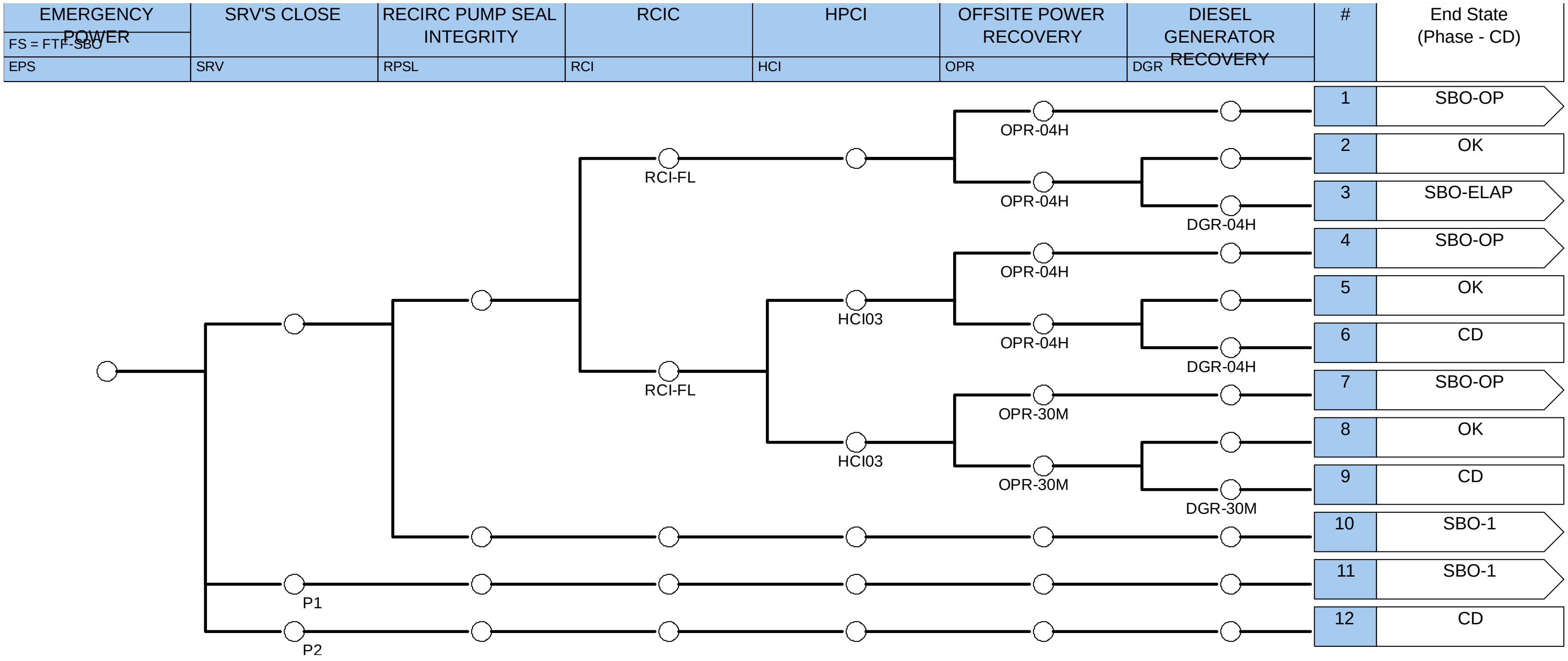


Figure B- 11. SBO ET.

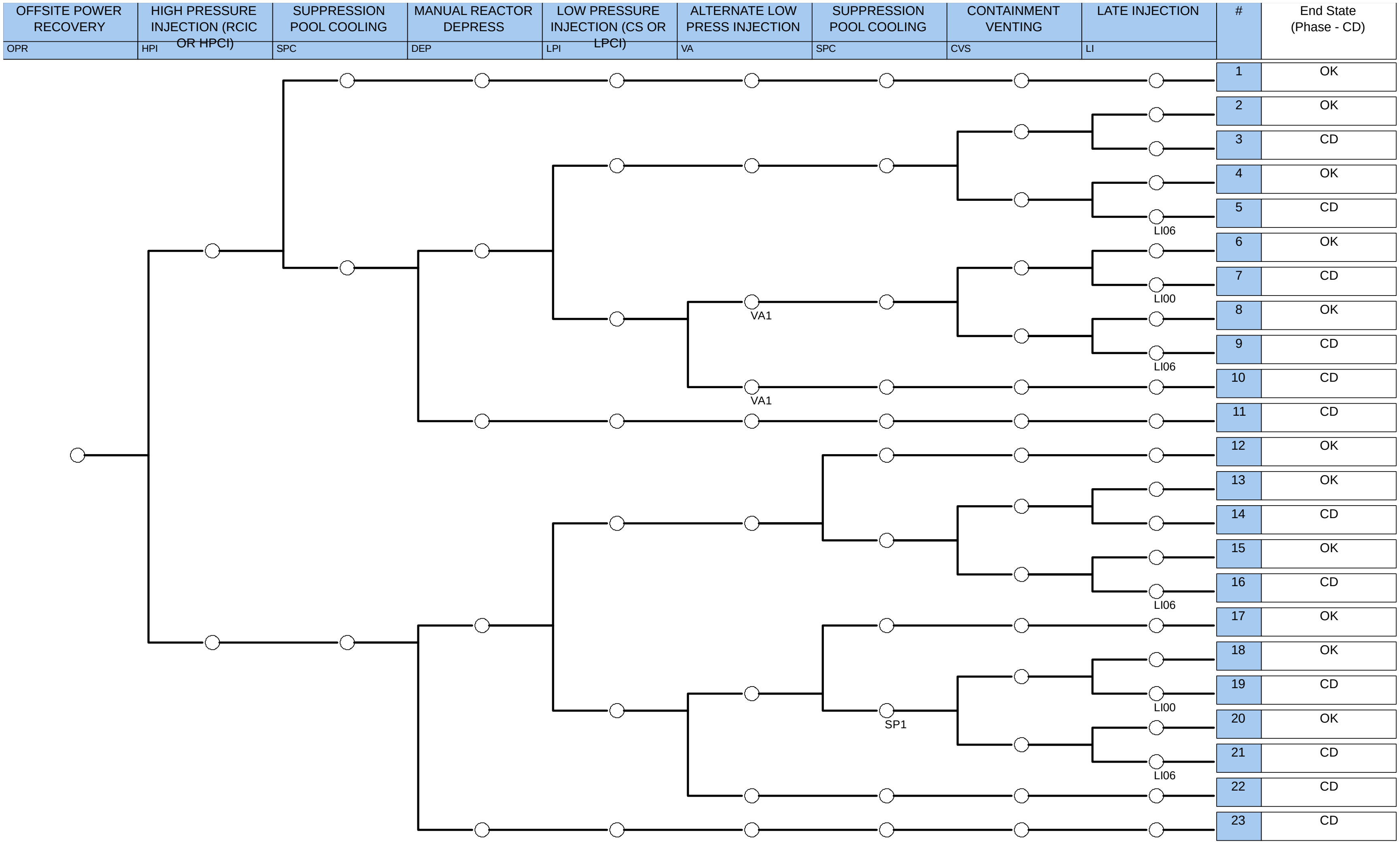


Figure B- 12. SBO-OP ET.

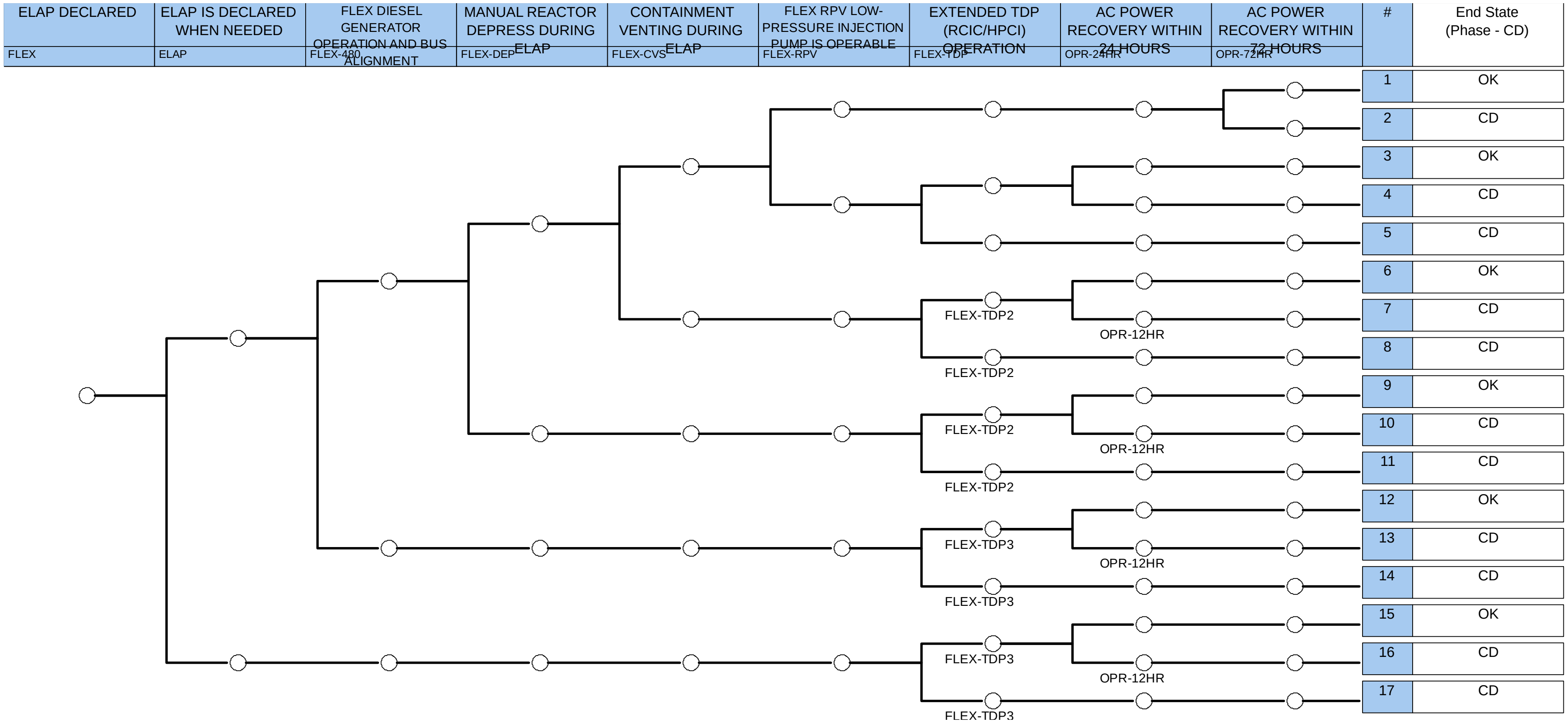


Figure B- 13. SBO-ELAP ET.

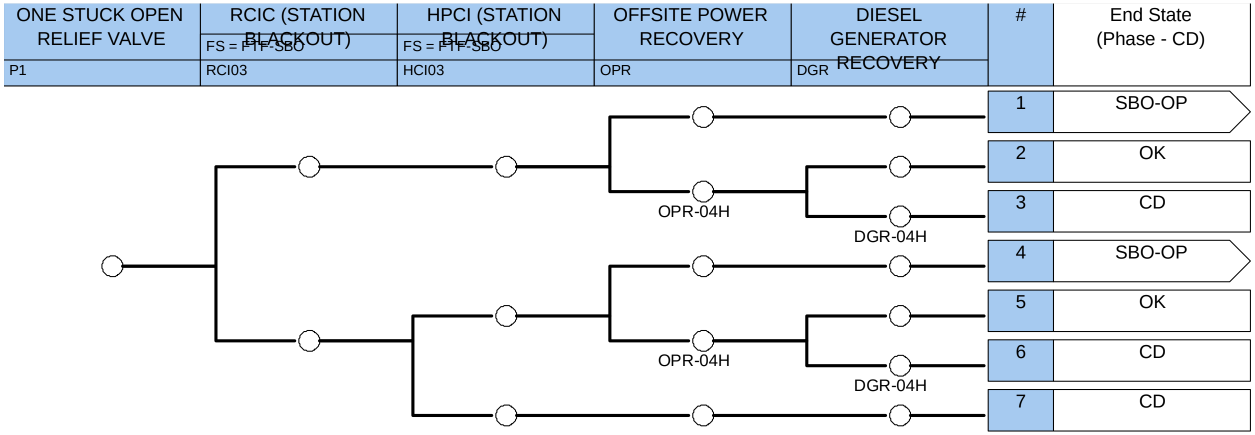


Figure B- 14. SBO-1 ET.

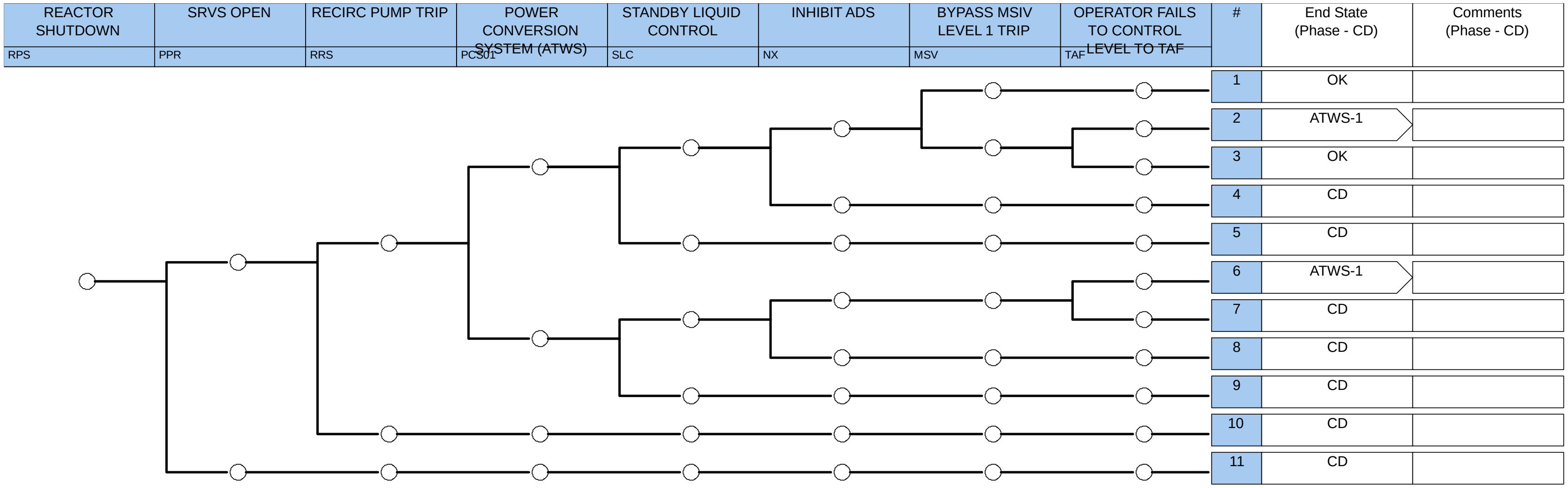


Figure B- 15. ATWS ET.

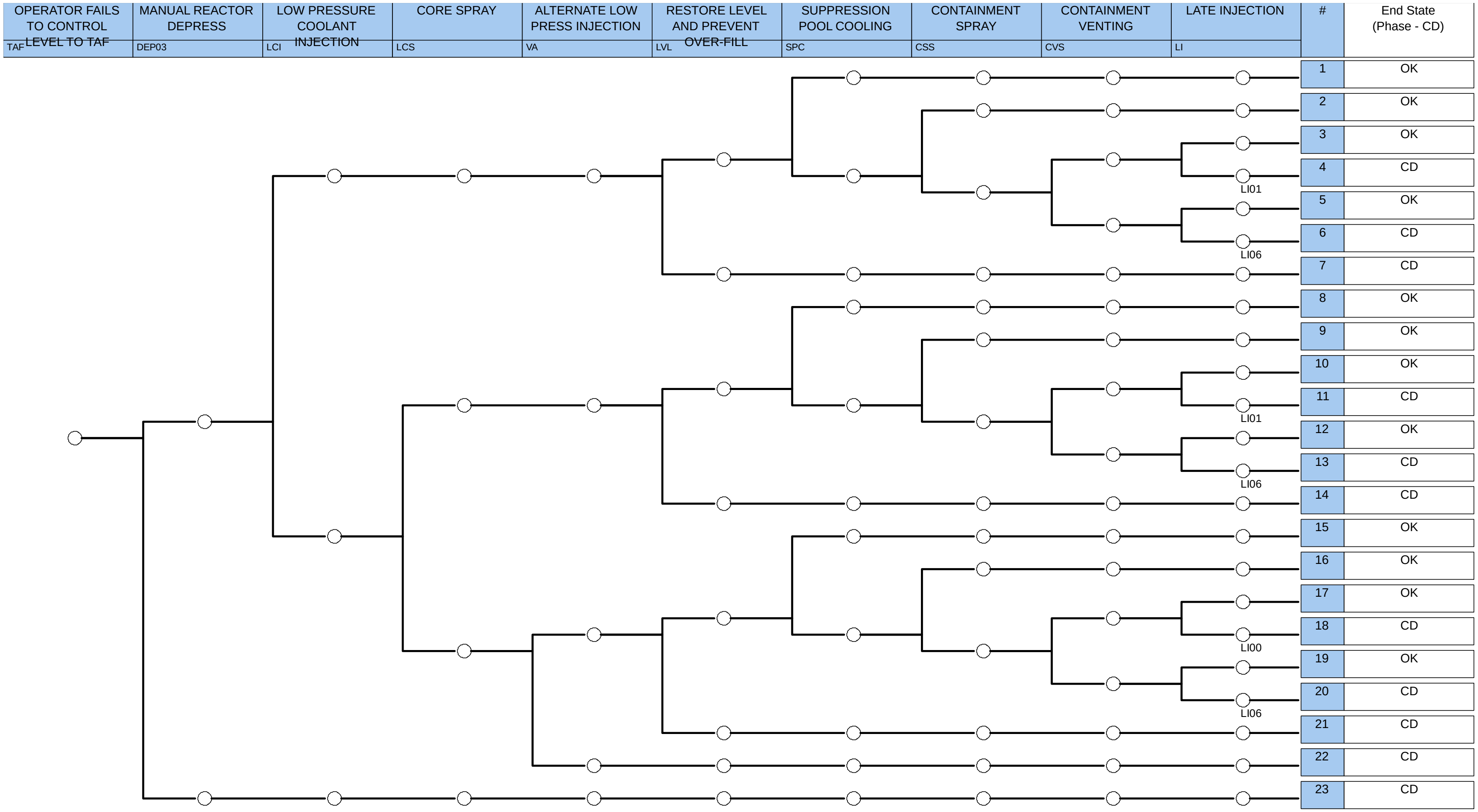


Figure B- 16. ATWS-1 ET.

Appendix C: FMEA Results

The FMEA results for BWR and PWR are presented on the following pages.

Table C- 1. Nuclear power plant based FMEA results (ranking scale from 1-10).

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for NPP**[4]	**General Notes**
External Power	Loss of offsite power	H2 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 is 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.
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.
Spent fuel storage (dry)	Cask tip-over due to overpressure, cask structural degradation	H2 detonation at HTEF	S = 7 F = 1 D = 1 **Total = 7**	Possible damage to storage building, if used. H2 Facility must have sufficient separation such that dry casks cannot be damaged.
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.	H2 detonation at HTEF	S = 5 F = 1 D = 1 **Total = 5**	Possible seismic upset to pipeline to ultimate heat sink.
H2 in NPP process	Increased levels of H2 in steam return	H2 piped back to NPP	S = 1 F = 1 D = 5 **Total = 5**	H2 levels are low and are already in risk assessments of applicable NPPs.

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[4] Risk Priority Number acronyms: S = Severity, F = Frequency, and D = Detection (1 = easy)

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for NPP[4]**	**General Notes**
Spray pond	Degradation of ultimate heat sink	H2 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	H2 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.	H2 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.
Forced air cooling for non-safety buildings	Damage and/or loss of NPP building HVAC equipment. Reactor building, admin building, etc.…	H2 detonation at HTEF	S = 2 F = 1 D = 1 **Total = 2**	Can affect human operations. May have to shut down reactor.
NPP & H2 administrative support	Damage to staffs' cars, office buildings and equipment	H2 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.
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.
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	H2 detonation at HTEF	S = 0 F = 1 D = 1 **Total = 0**	As sited at calculated safe distance NPP to HTEF.
Critical structure integrity	Damage to reactor building walls	H2 detonation at HTEF	S = 0 F = 1 D = 1 **Total = 0**	As sited at calculated safe distance NPP to HTEF.

Table C- 2. High temperature electrolysis facility based FMEA results (ranking scale from 1-10)

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for H2 Plant**[5]	**General Notes**
Hydrogen Transport by Truck	H2 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.
H2 Storage at plant	H2 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.
H2 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.
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 = 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	H2 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.

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[5] Risk Priority Number acronyms: S = Severity, F = Frequency, and D = Detection (1 = easy)

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for H2 Plant**[5]	**General Notes**
H2 Production	Electrolysis stacks damaged/toppled if stacked	H2 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 H2 would be halted. Design of facility stacking to wind/seismic codes minimizes this hazard.
Multiple	H2 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 H2 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.
H2 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.
Thermal energy delivery to hydrogen plant	Nucleide 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.

Process Function	**Hazard/Effect**	**Potential Causes/ Mechanisms of Failure**	**RPN for H2 Plant[5]**	**General Notes**
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 (ranking scale from 1-10)

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Public**[6]	**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.

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[6] Risk Priority Number acronyms: S = Severity, F = Frequency, and D = Detection (1 = easy)

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Public[6]**	**General Notes**
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.
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.
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.

Process Function	**Hazard/Effects**	**Potential Causes/ Mechanisms of Failure**	**RPN for Public[6]**	**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

Appendix D: Hydrogen Safety Analysis Supporting Information

This analysis documents the necessary modifications of [15] to evaluate a 100, 500, and 1000 MW_{nom} HTEFs. Note, the consequence evaluation utilized a deterministic methodology to evaluate the overpressure impact from a range of different distances.

System Leak Frequency

The leak frequency of the facility was calculated from the bottom-up component leak frequencies. A Bayesian statistical analysis 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 below in Table D- 1.

Table D- 1. Component Leak Frequencies [15]

Component	**Leak Size**	**Generic Leak Frequencies**				**Hydrogen Leak Frequencies**			
		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

Component	Leak Size	Generic Leak Frequencies				Hydrogen Leak Frequencies			
		Mean	**5th**	**Median**	**95th**	**Mean**	**5th**	**Median**	**95th**
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
	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

Table D- 2. HTEF Component Quantities Summary

Component	Quantity for 1150 MW HTEF	Quantity for Modular 25 MW unit	Quantity for 100 MW HTEF
Compressor	92	2	8

Cylinder (Vessel, Intercooler, Separator, Heat Exchanger)	874	19	76
Joint (Tee, Elbow, Reducer, Expander)*	150	3	24
Pipe	7,360	160	640
Pump/Blower	276	6	24
Valve	966	21	84

* There are a total of 12 joints in the system that are independent of the modules