Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant – Part 2: Hazards Assessment and PRA

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Abstract: The profitability of existing nuclear power plants (NPPs) can be enhanced by using excess thermal energy to supply industrial processes. While the decision to modify the NPP to supply thermal energy externally to the plant is an economic one, the licensing permission for the modification is based on safety. To investigate the safety acceptance for such a modification, two generic probabilistic risk assessment (PRA) models were developed in this study to evaluate the effect on safety of the addition of a heat extraction system (HES) to a light water reactor (LWR). The two PRA models are for a pressurized water reactor (PWR) and a boiling water reactor (BWR), respectively.

The introduction of a HES has the goal of providing heat that would normally be discarded to be used for new revenue generation through processes such as making hydrogen. For example, this HES module could feed process heat to a High Temperature Electrolysis Facility (HTEF). The PRAs used in this assessment of the HES are generic meaning the details of the analysis are for a hypothetical facility. A Failure Mode and Effects Analysis (FMEA) was performed to identify and screen the possible hazards due to the addition of the hydrogen production system. Hydrogen cloud and high-pressure jet detonation events were studied in relation to their contribution to components/structures fragility. A sensitivity analysis was performed to investigate the effect of several HES design options and distance to the nuclear reactor complex.

The results of the PRA indicate that application using the U.S. licensing approach in 10 CFR 50.59 is justified because of the minimal increase in initiating event frequencies for all design basis accidents, none exceeding 6%. The PRA results for core damage frequency (CDF) support the use of Regulatory Guide 1.174 as further risk information that supports a change to the plant. Further insights provided through hazard analysis and sensitivity studies confirm that the safety case for licensing an HES addition and an HTEF sited at one km from the nuclear power plant is strong. Note that unique site-specific and hydrogen production characteristics could alter these conclusions.

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1. INTRODUCTION

A detailed introduction of the need for a probabilistic risk assessment (PRA) and its components was presented in Part 1 [1]. System descriptions and hazards were identified. The assumptions of the model were listed driven by hazards analysis, current knowledge of the heat extraction system (HES) and high temperature electrolysis facility (HTEF), and the generic nature of the model. Fragilities of nuclear power plant (NPP) components were listed in pounds per square inch (psi). Consequences of a hydrogen detonation were presented as an overpressure in psi at the 1 km assumed separation distance between the NPP's most fragile component, transmission towers in the switchyard, and the HTEF.

Part 2 of this paper continues the presentation of the PRA to include the assessment of the hazards and the use of PRA to determine the effects on design basis accident initiating events (IE) and core damage frequency (CDF) in support of licensing pathways for the proposed changes to the NPP. A summary of work and opportunities for future research is also discussed.

2. IDENTIFIED HAZARDS ASSESSMENT

2.1 Hydrogen Detonation at the HTEF

The hydrogen detonation at the HTEF is the focus of the study performed by Sandia National Laboratories (SNL) [2]. Two types of detonations were considered: a high-pressure jet detonation and an accumulated cloud detonation. The leak frequency was determined by analyzing the piping and instrumentation diagrams (P&IDs) for the proposed pilot HTEF used for this project using industrial leak rate data for the individual components. The overall leak rate for leak sizes scaled from 1 = full line break is listed in [1] Table 3. The overpressure felt at the NPP from a high-pressure jet leak detonation, or a hydrogen cloud accumulation detonation was determined based on 15 leakage scenarios. No credit was given for attenuation of the shock wave made by buildings, wooded areas, or other topography. The bounding case presented in [2] used the largest leak size, denoted 1.0, and therefore this frequency (5.2E-02 /y) was 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. According to [3] the highest probability of detonation of a hydrogen leak in air, given an ignition source, is 0.35. This value was used for the determination of detonation frequency, given a leak, in the PRA model.

2.1.1 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 at the strength calculated. The overpressure from a maximum credible accident (MCA) scenario at 1 km distance from a high-pressure jet detonation is 0.056 psi [2]. The total fragility of switchyard components resulting from wind pressure and tornado-generated missiles is listed in [1] Table 1. This fragility data is used to determine the failure probability of these components when hydrogen detonation event occurs. The fragility data points are shown in Figure 1.

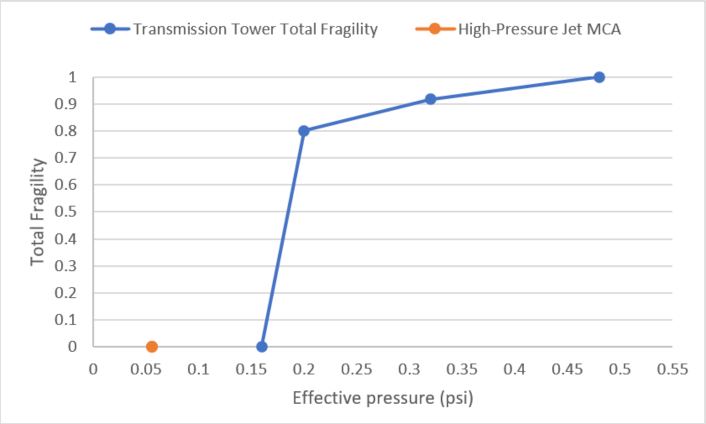

Figure 1. Switchyard components fragility as a function of wind pressure.

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 [4]. For reference, windows will break at an incident overpressure between 0.15 and 0.22 psi [5]. As highlighted in Figure 1, the damage probability of the most fragile component due to an MCA high pressure jet detonation scenario at 1 kilometer away is negligible. Therefore, the high-pressure jet detonation is not considered a safety concern in the PRA.

2.1.2 Hydrogen Cloud Detonation

The hydrogen cloud detonation frequency is determinant on the ability of to allow the hydrogen to accumulate within the building. This is determined by the failure of the building ventilation system to vent the leak to atmosphere and the failure of human action to isolate the leak within the specified time noted in [2]. For the MCA, this time is 120 minutes. The human action probability of failure (HTEF_XHE_LK) was determined using the human reliability analysis methodology (SPAR-H) [6] to be conservatively 1.0E-2, given nominal time to perform the action and all other performance shaping factors listed as nominal. A less conservative approach, giving expansive time to perform the action was calculated as a probability of failure of 1.0E-04 using the same methodology. The failure of all modes of an industrial building ventilation system (HTEF_VENT_HR) was noted to be 2.4E-05/h in [7]. The probability of detonation, given a leak (HTEF_LK_DET) is 0.35, as noted above. These probabilistic events, along with the yearly frequency of 5.2E-02/y for the full leak creating the MCA (HTEF_H2_LK), were modeled in a fault tree to determine the frequency per year of the cloud detonation MCA event. Mathematically, the frequency per year of a hydrogen cloud detonation induced switchyard centered loss of offsite power (LOOP) is the equation:

$$\begin{gathered} \mathit{IE\_LOOP\_SC\_H2\_CLOUD} = \\ \mathit{HTEF\_VENT\_HR} * \mathit{HTEF\_LK\_DET} * \mathit{HTEF\_XHE\_LK} * \mathit{HTEF\_H2\_DET\_SC} * \mathit{HTEF\_H2\_LK} \end{gathered} \tag{1}$$

The resulting frequency with a dedicated building ceiling ventilation is 4.2E-09/y. This is 7 orders of magnitude below the switchyard-centered LOOP IE frequency of 1.3E-02/y for both the boiling water reactor (BWR) and pressurized water reactor (PWR) models described below and five orders of magnitude below the initiating event for loss of service water result of 1.8E-04/y in the BWR model. The results of the IE fault tree were used to screen out the hydrogen cloud detonation as a safety concern in the PRA.

2.2 HES Inisolable Steam Pipe Rupture

An increased IE frequency of a large steam line break (IE_MSLB) is the most common hazard introduced by adding the HES to the NPP. The HES P&ID ([1], Figure 1) shows there are two isolation valves for the HES set in a series configuration. The success of these valves is the first line of defense of a steam line rupture within the HES after the NPP's main steam isolation valves (MSIVs). Rupture of the isolation valves was also a possibility that was modeled. After the isolation valves, all the other active components in the P&ID were evaluated in the fault tree of the HES. The result of the fault tree (IE_HES_SYS), of which is too lengthy to denote in equation form in this paper, was added to the IE for a large steam line break:

$$\mathit{IE\_MSLB\_NEW} = \mathit{IE\_MSLB} + \mathit{IE\_HES\_SYS} \tag{2}$$

2.2.1 HES Heat Exchanger Leak

Two types of heat exchanger leaks were considered for the PRA. One was a slow leak that is not a prompt safety concern to the operation of the NPP, while the other was a heat exchanger rupture.

Slow Leak of an HES Heat Exchanger: The heat-transfer loop to the HTEF will always be operating at lower pressure than the NPP steam loop through the HES. This prevents the contamination of the NPP steam loop. Small leaks in the heat exchanger may contaminate the thermal power delivery heat-transfer loop to the HTEF. This event can cause a cleanup problem if there is enough radioactivity transferred to the heat-transfer loop. For most NPPs this will not be a problem. PWR steam loops are less likely than BWRs to have radioisotopes of any measure. Still, this a unique potential hazard to LWR NPPs considering this modification. There are prevention, detection, and mitigation measures that would need to be in place to monitor for and react to any small leaks. This hazard could cause economic issues for the cleanup, including shutdown of the reactor, and cause environmental concerns in the public. This study was concerned with reactor safety and did not consider the architecture of a representative system.

Rupture of an HES Heat Exchanger: There are two HES heat exchangers ([1], Figure 1). HES-EHX-1 heats the heating medium (steam or heat transfer fluid) to its operating temperature. HES-EHX-2 pre-heats the returning heating medium and helps to chill NPP steam as after it exits HES-EHX-1. An HES heat exchanger rupture failure maps to the HES large steam line break event and is treated as an event within the IE fault tree (IE_HES_SYS, Equation 1).

2.2.2 Ignition of Leaked Heat-Transfer Medium

The use of steam as the heat-transfer medium screens this hazard out from consideration. The PRA report [8] details the properties of the heat transfer fluids investigated for possible future use.

2.2.3 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. The failure mode and effects analysis (FMEA) team determined that LWR NPPs can withstand up to 30% load drop without having to trip the reactor. This screened out one of the FMEA hazards postulated, that a prompt load drop felt by the NPP is pushed to the turbines resulting in a turbine trip, even without the successful closing of the HES isolation valves.

2.3 Incorporation of Hazards into the Existing Generic PRAs

Two generic NPP PRAs were prepared, one a PWR and the other a BWR. To remain generic, external events other than those created by the addition of a HTEF near the NPP were not included in the model. A Mark I containment BWR and a two-loop PWR were modeled. From the generic PRA starting point, modifications were made to the logic models for cases where systems might be affected by the addition of the HES and the HTEF. External events were considered a result of an HTEF hydrogen detonation and was represented by an increase in the switchyard-centered LOOP frequency. The external hydrogen detonation event was also analyzed for inclusion in the PRA on its own as potentially damaging to critical structures.

2.3.1 Generic PWR Model

The addition of an HES system 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 was an increased probability for steam leakage through the new system. A break in the main steam line (MSLB) causes the loss of 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 system supplies feedwater to the steam generators while the main steam/feedwater line is isolated. If the main steam line cannot be isolated, the Auxiliary Feedwater system cannot inject water due to the high pressure in the line and the High-Pressure Injection system is used in its place. An initiating event fault tree was created to model this hazard by summing the existing MSLB initiating event with the yearly failure frequency of the modeled HES. Mathematically, the new initiating event frequency is given by the equation:

$$\mathit{IE\_(MLSB\_NEW\ )= IE\_MLSB+HES\_(FAULT\_TREE\ )-(IE\_MLSB*HES\_(FAULT\_TREE\ ))} \tag{3}$$

Additionally, the existence of a hydrogen production plant near the NPP may create another hazard (i.e., hydrogen detonation). 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 triggers a LOOP that causes a transient to the reactor.

The switchyard component may fail under the following circumstances: a leak occurs that accumulates a cloud of hydrogen (HTEF_H2_LK). The yearly frequency of a full hydrogen pipe rupture in the HTEF is 5.2E-02 and this MCA leakage is used to accumulate the hydrogen within 2 hours. The plant operator fails to isolate the leakage within the 2 hour time required to accumulate the MCA volume of hydrogen (HTEF_XHE_LEAK), the dedicated ceiling ventilation fails to disperse the hydrogen to the atmosphere (HTEF_VENT_HR), and a detonation occurs given that the hydrogen cloud has accumulated (HTEF_LK_DET). This MCA scenario is assumed to be the bounding accident to damage the switchyard components. The hydrogen ignition probability (HTEF_LK_DET) is a function of hydrogen leakage rate [3]. A detonation probability value of 0.35 (the highest probability listed in [3]) is used for this analysis. This scenario ignites a total of 13.2 kilograms of hydrogen and impacts an overpressure of 0.39 psi to the nuclear plant structures located 1 km from the hydrogen plant. This overpressure will fail the switchyard components with a statistical probability of 0.95 (HTEF_H2_DET_SC) and create a LOOP event.

The fault tree discussed in hydrogen cloud detonation hydrogen cloud detonation is logically OR'd (mathematically added) to the original switchyard centered LOOP (IE_LOOPSC) and is used as the new initiating event in the PRA. Mathematically, the new initiating event is the equation:

$$\mathit{IE\_LOOPSC\_NEW} = \mathit{IE\_LOOPSC+(HTEF\_VENT\_HR*HTEF\_LK\_DET*HTEF\_XHE\_LK*HTEF\_H2\_DET\_SC*HTEF\_H2\_LK)} \tag{4}$$

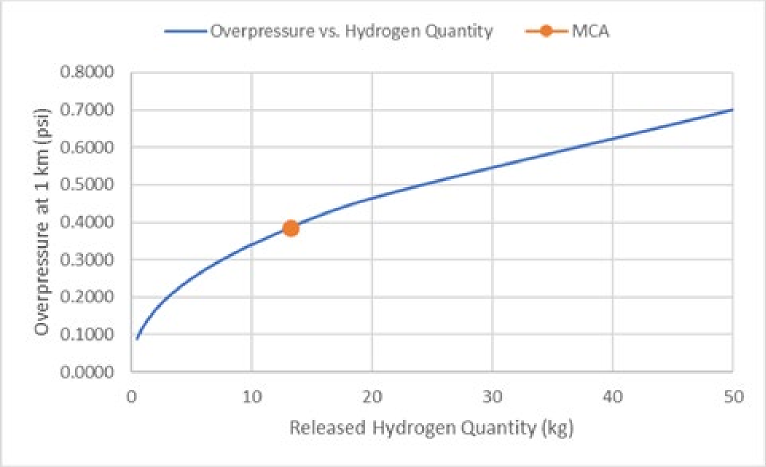

Figure 2. Overpressure at a distance of 1 km due to hydrogen detonation.

It was 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 taken 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 actuation timing of 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 to 120 minutes, the total fragility may be calculated by uniformly sampling the quantity of released hydrogen in Figure 2 up to the MCA scenario and performing a look-up conversion of the detonation's overpressure to find the switchyard fragility using Figure 1. The total switchyard fragility estimated using a Monte Carlo simulation of 10,000 samples is found as 0.76, which is less than the 0.95 fragility for the MCA event. For that reason, it is reasonable to accept that the MCA detonation assumption is conservative.

2.3.2 Generic BWR Model

Like the PWR, the HES system in the BWR taps steam from the main steam line after the MSIVs. A loss of up to 5% of steam flow rate due to a leakage event in the HES may lead to a general transient event. For a BWR, the transient can be mitigated safely if reactor power generation is shut down, the offsite power (or emergency 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 high pressure injection system is activated followed by suppression pool cooling. Without the automatic suppression pool cooling, operators need to depressurize the reactor manually and perform control rod drive injection.

The mitigation procedure for a steam line break in the HES system is dependent on the reactor protection system shutting the reactor down. If a steam line break in the HES system occurs, the core will be damaged if the Reactor Protection System (RPS) fails, or if the MSIVs fail to close. If both systems function properly, the mitigation tree transfers to the General Transient (TRANS) event tree. However, since the TRANS event tree is used as is, logic rules are applied in the PRA to customize the tree based on the initiator (i.e., a steam line break in the HES). These rules instruct the PRA software to set the RPS top event within the TRANS event tree to a success state so as not to sample the RPS top event twice within the logic chain. The use of rules allows the TRANS event tree to be used normally for other sequences.

Meanwhile, when the TRANS event tree is activated after the MSIVs are closed, the Power Conversion System (PCS), which runs off the reactor steam after the MSIVs, is always off. Logic rules are used in the PRA to disable the PCS and PCS recovery fault trees within the TRANS event tree and any transfers to account for this operating state.

The BWR PRA models the HTEF hydrogen detonation event identically to the PWR PRA.

2.3.3 Sensitivity Studies

Several configuration sensitivity studies were conducted in the risk analysis including different HES design options and the use of a dedicated ventilation system in the HTEF. A complete list of design option sensitivity studies and their results can be found in [8]. The highest interest sensitivity study was the distance study between HTEF and the Switchyard. These results are included below.

3. PRA RESULTS

3.1 PWR PRA Results

PWR PRA results are summarized in Table 1. The initial IE frequency for MSLB in the PWR model 3.0E-4/year and the CDF from this event is 2.5E-7/year. With the installation of the HES system, the resulting frequency for this event is 3.2E-4/year, or an increase of 5.6% from the initial value. The new CDF is 2.7E-7/year, or an increase of 4.9% from its initial frequency.

For the switchyard-related LOOP event, the initiator frequency is determined by the operator's performance to seal the leak within 2 hours as the bounding time for the MCA event. If all the SPAR-H performance shaping factors are set at their nominal values, the operator's failure to isolate the leakage in 2 hours is 1E-2. With this value, and without the presence of a dedicated ceiling ventilation system to vent out the hydrogen leakage, the IE frequency increases slightly by 1% from 1.3E-2 to 1.4E-2. Even so, this estimate may be rather conservative, because 2 hours is a reasonably ample time to actuate a valve isolating the leakage [2].

Sensitivity analysis was performed to determine the benefit of adding a dedicated ceiling ventilation system to the hydrogen plant. A risk increase of 1% rise from the initial CDF was observed when there is no dedicated ceiling ventilation system to vent the leaked hydrogen.

Table 1. Summary of PRA results for PWR.

Risk metric	**Case**	**Initiating Event Frequency (/y) (Δ%)**	**Core Damage Frequency (/y)**
Steam line break	Nominal	3.0E-4	2.5E-7
Steam line break with HES system	Base assumptions	3.2E-4 **(+6 %)**	2.7E-7 **(+5 %)**
Switchyard-related LOOP frequency	Nominal	1.3E-2	2.7E-7
Switchyard-related LOOP with HES system, conservative SPAR-H timing, without dedicated ceiling ventilation system	Base assumptions	1.4E-2 **(+1%)**	2.8E-7 **(+1%)**
Switchyard-related LOOP frequency with HES system, conservative SPAR-H timing, and dedicated ceiling ventilation system	Sensitivity	1.3E-2	2.7E-7

Based on the results in Table 1, the total plant CDF is calculated using the conservative assumption that 2 hours is the nominal time to locate and seal hydrogen leakage (a conservative SPAR-H timing) and in which the hydrogen plant does not have a dedicated ceiling ventilation system. Furthermore, the base design of the HES system is selected, and the base assumptions listed in [1] Section 3.2 are followed. These results are shown in Table 2. The flexible NPP operation with an HES system increases CDF by 5.4E-7 (7%).

Table 2. Risk metric for PWR.

Configuration	**Total CDF (/y)**
NPP without HES	8.3E-6
NPP with HES	8.8E-6

3.2 BWR PRA Results

PRA results for the reference BWR reactor are summarized in Table 3. The addition of steam line break IE frequency to the existing general transient initiator is trivial. Likewise, the additional CDF due to steam line break in HES system is less than 1%. Meanwhile the IEs related to a switchyard-induced LOOP are the same with the PWR model because such events are indifferent to the reactor types, but are a function of the geographical region in which the reactor resides in. The increase in CDF due to switchyard-related LOOP resulting from the hydrogen MCA event is negligible.

Sensitivity analysis was performed to determine the benefit of adding a dedicated ceiling ventilation system to the hydrogen plant. The highest risk increase of 1% rise from the initial CDF is observed when the SPAR-

H timing is set at the nominal value and there is no dedicated ceiling ventilation system to vent the leaked hydrogen. These results are summarized in Table 3.

Table 3. Summary of PRA results for BWR.

Risk metric	**Case**	**Initiating Event Frequency (/y) (Δ%)**	**Core Damage Frequency (/y)**
General transient frequency (steam line break is modeled within general transient for the BWR)	Nominal	7.4E-01	3.9E-06
Steam line break with HES system	Base assumptions	1.7E-5 **(+2E-3%)**	8.0E-10 **(+2E-2%)**
Switchyard-related LOOP IE frequency	Nominal	1.3E-02	5.8E-7
Switchyard-related LOOP frequency with HES system, conservative SPAR-H timing, without dedicated ceiling ventilation system	Base assumptions	1.4E-2 **(+1%)**	5.9E-7 **(+1%)**
Switchyard-related LOOP frequency with HES system, conservative SPAR-H timing, and dedicated ceiling ventilation system	Sensitivity	1.3E-02	5.8E-7

Using the results in Table 3, the plant risk measures are calculated on the conservative assumption that 2 hours is the nominal time to locate and seal hydrogen leakage (a conservative SPAR-H timing) and in which the hydrogen plant does not have a dedicated ceiling ventilation system. The base design of HES system as discussed in the PWR results section above and the base assumptions listed in [1] Section 3.2 are also selected for this analysis. The results are shown in Table 4. It is found that the total CDF increases by 1.0E-8 (4E-2%) when a BWR NPP is coupled with a hydrogen production facility.

Table 4. Risk metric for BWR.

Configuration	**Total CDF (/y)**
NPP without HES	2.5E-5
NPP with HES	2.5E-5

3.3 Extended Sensitivity Analysis Results

3.3.1 Distance between HTEF and Switchyard

The hydrogen detonation event included in the PRA is the cloud detonation event in which leaked hydrogen accumulates indoors for 2 hours before it finally ignites and detonates. The frequency of occurrence of this event increases the IE and CDF frequencies by 1%. The distance of the HTEF to the NPP is assumed as 1 km in this study, following the overpressure analysis conducted by SNL [2]. This shows that 1 km is a safe separation distance based on a set of conservative assumptions. An additional sensitivity study was conducted to analyze the effect of separation distance on the most fragile component in NPP switchyards, transmission towers, of which the failure causes a switchyard-induced LOOP. Figure 3 shows the overpressure and total fragility curves of the transmission tower as a function of separation distance between the hydrogen and the switchyard. At 1 km the fragility is 0.95. the distance around 845 meters marks the critical fragility for switchyard components, below which their fragility is 1.

When the hydrogen plant is distanced less than 845 meters, the switchyard-related LOOP frequency using the selected assumptions in [1] Section 3.2 increased slightly by 1E-5, from a 1.0% increase at 1 km separation distance to a 1.1% increase at 845 m or less. However, it does not imply that the separation distance can be reduced freely, as there is another hydrogen denotation event that may affect plant safety considerably at close distances.

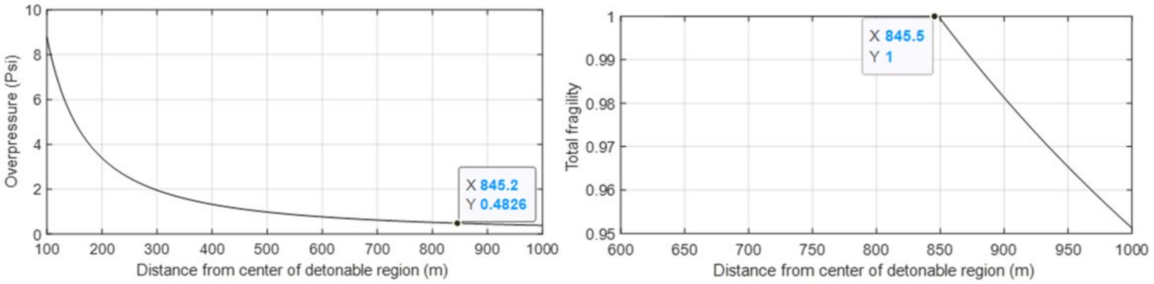

Figure 3. MCA overpressure (left) and total switchyard fragility (right) as a function of separation distance between the hydrogen and the nuclear plant.

The high-pressure hydrogen jet detonation event was excluded from the PRA ignition on the basis that it cannot create a significant overpressure to damage a transmission tower at 1 km separation distance as shown in Figure 1. However, if the separation distance is reduced, the overpressure from the high-pressure hydrogen jet may damage the transmission tower and create a LOOP event. For that reason, a sensitivity analysis was conducted to find the minimum safe distance. The LOOP initiator fault tree was modified (Equation 5) to include the high-pressure jet event by adding the events which must occur to create the detonation and switchyard failure: the frequency of a full rupture of a hydrogen pipeline in the HTEF (HTEF_H2_LK), the detonation probability given a leak (HTEF_LK_DET), and the switchyard failure probability due to hydrogen jet explosion (LOOPSC_SC_JET_F). The switchyard failure probability due to jet detonation (LOOPSC_SC_JET_F) is initially set to 0 at a separation distance of 1 km. If a 15% increase in IE frequency is set as the safety limit following guidelines discussed in the 10 CFR 50-59 licensing discussion below, the LOOPSC-SC-JET-F event should have a probability of 0.11. Meanwhile, if a 5% increase in IE frequency is used such that the change in switchyard-related LOOP frequency is comparable to the increase in Steam Line break frequency, the probability for LOOPSC-SC-JET-F event can increase to 3.7E-2.

$$IE\_LOOPSC\_NEW = IELOOPSC + LOOPSC\_SC\_JET\_F * HTEF\_LK\_DET * HTEF\_H2\_LK \qquad (5)$$

SNL [2] assessed various hydrogen jet detonation scenarios and identified the most conservative scenario as a 200 mm break with a temperature of 50º C and pressure of 7 MPa. By combining data from this reference and Figure 1, a graph of transmission tower fragility versus the separation distance between the hydrogen plant and transmission towers is plotted in Figure 4. The data points for IE-LOOPSC-SC-JET-F to fulfill the 5% and 15% IE increase are highlighted on the plot. The figure suggests that a minimum separation distance lies at around the 450-meter mark to meet the safety criteria explained in the previous paragraph. When the transmission tower is spaced at least 500 meters away from the hydrogen plant, the LOOP risk due to high-pressure hydrogen jet detonation is nullified.

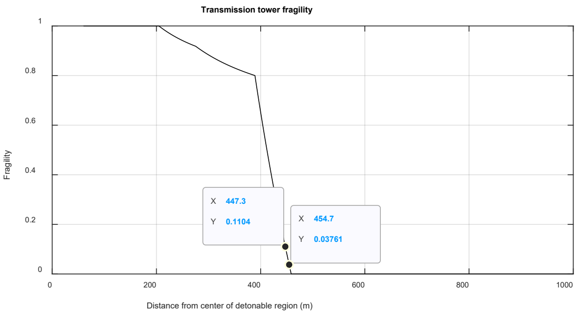

Figure 4. Fragility curve of transmission tower.

3.4 PRA use for Licensing Support

To implement the types of changes to a U.S. nuclear power plant described in this paper, the regulations managed by the U.S. Nuclear Regulatory Commission would be followed. Potential regulatory approaches could be modifications through 10 CFR 50.59 [9] where the changes would be evaluated via a design basis accident type of approach. Additionally, plant configuration change requests may be supported via RG 1.174 [10] where the plant PRA is used to help justify the modification. If neither of these are sufficient then a license amendment request (LAR) may be requested. A reference study commissioned by INL [11] noted criteria that need to be met in 10 CFR 50.59:

1. If the 10 CFR 50.59 [9] approach is used to consider the plant modification, the decision metrics considered are the impacts on the current design basis events. Changes that meet the eight criteria of 10 CFR 50.59 do not require additional NRC review and approval: 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 a structure, system, or component (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 (FSAR) (as updated) being exceeded or altered.

8. Result in a departure from a method of evaluation described in the FSAR (as updated) used in establishing the design bases or in the safety analyses.

The PRA hazards analysis did not find adverse impacts to SSCs in the list. The study noted that minimal increase is traditionally understood to be less than 10%. The PRA found the largest increase in a DBA yearly IE frequency to be 6% (Large Steam Line Break for the PWR, Table 1), thus meeting the criteria for 10 CFR 50.59.

If the RG 1.174 [10] approach is used in support of the plant modification, one of the decision metrics is 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 large early release frequency.

As described in RG 1.174, CDF should be below 1E-5 overall and the change in overall CDF should be below a magnitude of 1E-5. Any plant which starts at a 1E-4 or more CDF requires less than 1E-6 increase in CDF to be considered. If these metrics are met, the NRC most likely considers this a small change which is 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.

As noted in Table 2, the generic PWR being considered for this study has a nominal CDF of 8.3E-06 /y and the new CDF after addition of the HES and HTEF is to 8.8E-06 /y for ΔCDF of 5.4E-07 /y, which is well within the most acceptable region of RG 1.174.

As noted in Table 4 (above), the generic BWR being considered for this study has a nominal CDF of 2.8E-05 /y and the new CDF after addition of the HES and HTEF is still 2.8E-05 /y for ΔCDF of 1.0E-07 /y, which is well within most acceptable region of RG 1.174.

4. CONCLUSIONS

Two generic PRAs for the addition of an HES addition to an LWR are performed, one for a PWR and one for a BWR. The results investigate the applicability of the potential licensing approaches which do not require a full NRC licensing review and summarizes the LWRS sponsored INL report [8]. The PRAs are generic, and some assumptions are made. Many conservative assumptions from a preliminary PWR PRA report [12] were eliminated using design data for both the HES and the HTEF. 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, none of which exceeds 10%. The PRA results for CDF support the use of RG 1.174 as further risk information that supports a change without a full LAR.

This PRA investigation outlines a successful pathway to follow when moving to the site-specific case. The hazard analysis performed to support the PRAs in this paper provides insights that built the nominal case of safety and identified some economic and non-safety hazards. Key findings were that the HES should be placed in its own building for protection of the turbine building SSCs should there be a large steam line rupture, the high-pressure jet detonation hazard at the HTEF can be screened out as a hazard based on the low overpressures experienced at 1 km, and a sensitivity study found that the minimum safe distance between the HTEF and the NPP (switchyard transmission towers) to be 500 meters.

Additionally, using a dedicated ceiling ventilation at the HTEF and a less conservative time allotment to isolate the hydrogen leak added approximately 1.3% to the safety margin for the LWR licensing case, however the licensing safety case is strong even without these additions.

This paper confirms the safety case for licensing an HES addition and an HTEF sited at 1.0 km from the NPP is strong. The paper also concludes that the placement of a HTEF at 500 m is safe.

5. FUTURE RESEARCH OPPORTUNITIES

Interaction with industry through the U.S. Department of Energy Office of Nuclear Energy Light Water Reactor Sustainability Program (LWRS) Hydrogen Research Regulatory Review Group (H3RG) has highlighted several research areas that can help industry to develop PRA assisted licensing pathways:

- The existing SAPHIRE-coded PRA model can be translated to a prominent industry code,
- Modify the hazards analysis and model to match the current design of the HES and the HTEF as details become available,
- Analyze full or partial direct electrical coupling of the NPP and HTEF,
- Analyze seismic upsets to the NPP as a result of a hydrogen detonation,
- Analyze the effects of engineered blast barriers on the safe minimum separation between the NPP and HTEF.

Continued interaction between the H3RG PRA Subcommittee and the national laboratories PRA team can improve the existing generic PRAs and help industry develop site-specific PRAs

6. ACKNOWLEDGEMENTS

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