Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant – Part 1: Hazards Analysis

Kurt G. Vedros[a], Robby Christian[b], Austin Glover[b], Curtis L. Smith[a]
[a] Idaho National Laboratory, Idaho, USA, kurt.vedros@inl.gov
[b] Idaho National Laboratory, Idaho, USA, robby.christian@inl.gov
[c] Sandia National Laboratories, Albuquerque, USA, amglove@sandia.gov
[d] Idaho National Laboratory, Idaho, USA, curtis.smith@inl.gov

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 NPP is strong. Note that unique site-specific and hydrogen production characteristics could alter these conclusions.

1. INTRODUCTION

Penetration of various renewable power plants and low natural gas prices are threatening the profitability of already existing, paid off, nuclear power plants (NPPs). The Nuclear Energy Institute [1] reported that the total generating cost for nuclear energy of existing light water reactor (LWR) plants in 2017 was \$33.50/MWh. This relatively low operating cost is quite competitive to other energy sources. However, there are other economic factors that need to be considered due to the intrinsic nature of the LWR power generation process. In the U.S., LWR NPPs are typically run at full power during unfavorable over-supply electric market situations caused by fair weather and low electricity demands. This operational approach is caused by the desire to avoid reactor shutdowns which lead to time delays in restarting and stress on major components. On the other hand, NPPs generally have superior reliability which allows operators to continue running them without frequent shutdowns [2]. As a result, while the current LWR fleet consists of 10% of the U.S. operating *capacity* of electricity generation, it is consistently run at a much higher availability than other technologies and provides 20% of the total electricity sold in the U.S [3]. This is one of the benefits NPPs provide to the electric grid, which is not adequately compensated, thereby impacting their finances and sustainability in operating in such a baseload manner.

To increase the utility and profitability of the current fleet of LWR NPPs, the Light Water Reactor Sustainability (LWRS) Program, sponsored by the U.S. Department of Energy, is evaluating the feasibility of using heat from an NPP for use in other industrial applications. Steel manufacturing, chemical processing, desalination, and hydrogen production are examples of industrial applications that could utilize heat from an LWR NPP. The co-located industrial facility will benefit from lower cost process heat and the NPP will benefit from an income from its consistent production of thermal energy. The feasibility of installing a modification of an LWR NPP to export process heat to an industrial facility is broken into two parts: economic viability and the safety case. The economic benefit will determine if the modification is desired. The safety case will determine if the modification is allowed through licensing by the U.S. Nuclear Regulatory Commission (NRC). This paper concentrates on the probabilistic safety case of the use of LWR-extracted heat in hydrogen production by electrolysis of water.

For the suggested change to the LWR design and operation to be approved, the NRC requires a demonstration that the safety of the NPP will not be affected adversely [4, 5]. 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 probabilities of what can go wrong and the consequences of those undesired events. The quantitative results of the PRA are compared to guidelines set by the NRC which determine if the design and operation are safe enough for approval or if changes need to be made to increase its safety.

Prior studies have investigated the safety of a hydrogen production plant attached with an NPP. Reference [6] proposes a high-pressure hydrogen leak model and studies hydrogen's flammability after dispersion. Shi et al [7] proposes a new stochastic Bayesian Regularization Artificial Neural Network (BRANN) for hydrogen explosion risk analysis. Sandia National Laboratory (SNL) has also compiled data and methods to assess the safety of hydrogen systems in a software package named HyRAM [8]. The software integrates deterministic and probabilistic models for quantifying accident scenarios, predicting physical effects, and characterizing the impact of hydrogen hazards, including thermal effects from jet fires and overpressure effects from deflagration in enclosures. These studies are useful in modeling events of hydrogen gas leakage and explosion. However, there is a need to integrate these events into a plant PRA model to quantify the overall PRA of a combined operation of a nuclear and a hydrogen plant.

Idaho National Laboratory (INL) has investigated the minimum safe distance between a hydrogen production facility and an advanced-design NPP [9] and a pressurized water reactor (PWR) coupled with a hydrogen production facility using conservative assumptions [10]. This paper complements the LWRS sponsored INL report INL/EXT 20 60104, "Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant" [11]. The INL report used the most current design knowledge of a heat extraction system (HES) and high-temperature electrolysis facility (HTEF) to build generic PRAs for a boiling water reactor (BWR) and PWR that model the risk of core damage by quantifying the CDF associated with removing heat from the process steam to supply to a hydrogen HTEF. Within the individual PRA, the HTEF is treated as both a potential internal and external event hazard upon the LWR. A hazard analysis is performed to identify the hazards introduced by the HES and HTEF. The jurisdictional boundaries of the two facilities are used to help determine the categorization of internal and external events upon the NPP.

The initiating event (IE) frequencies associated with the addition of the LWR's HES and the HTEF center around an increased probability of a steam leak from the additional loop. The external event of most interest from the addition of an HTEF near an NPP is the potential for large detonation accidents where the overpressure impulse (i.e., shock wave), fire, or shrapnel impacts the reactor building or other critical structures on the site. These risks and others identified by the hazard analysis are evaluated through engineering analysis to determine IE frequencies that are used in existing and potential new event trees of the PRA. Fault trees are modified within the PRA to model any effects on the mitigating systems of the LWR. The results of the IE frequencies are compared against the guidelines set in 10 CFR 50.59 [4] and the CDF calculated from the PRA are compared against the guidelines set in RG 1.174 [5]. The applicability of the results to the licensing path using 10 CFR 50.59 and RG 1.174 are shown.

2. NPP WITH HES AND CO-LOCATED HTEF SYSTEM DESCRIPTION

The generic PRAs and hazards analysis started with the safety logic modeling of the HES. The HES will be integrated with the NPP main steam at an outlet downstream from the NPP's main steam isolation valves (MSIVs). At the time of the PRA Report, there were two designs considered for the HES. The first design was a two-phase-to-two-phase transfer design where the heat-transfer medium in the thermal power delivery (TPD) loop enters a vapor phase when heated to operating temperatures. The other design was a two-phase-to-one-phase transfer where the heat-transfer medium stays in the liquid phase. Steam-to-steam heat transfer will always use the two-phase-to-two-phase design. Heat-transfer fluids, many times incorrectly referred to as "heating oil," can be used in two-phase or single-phase operating states depending on their physical characteristics and the desired operating temperature. Note that there was no actual HES system at the time of this research and therefore these were conceptual designs based on those used in [12]. A two-phase-to-two-phase design is the more likely of the two systems, given the advantages and familiarity of using steam. It also has more components and is the more conservative choice for modeling, therefore it was assumed for the analysis. The analysis resulted in an increase in the existing IE frequency for an un-isolable main steam line break, among other considerations.

2.1 Two-Phase-to-Two-Phase HES Design

A piping and instrumentation diagram of the proposed HES line for steam in the TPD loop is shown in Figure 1 as adapted from [12]. The nuclear plant's steam line (main steam header) taps steam from the main steam line downstream from the MSIVs. The steam condition available for extraction at the main steam header is saturated steam with a total mass flow rate of 5.8×10^6 kg/hr (1.3×10^7 lb/hr) at 69.5 bar (1,008.5 psia). HES-1 is the main control valve for the HES line, and therefore has the largest effect on reactivity control. During steady-state operations, the steam in the HES line is condensed to avoid sending high-pressure steam to the condenser, which would decrease plant operating efficiency. The extraction heat exchangers required for heat transfer to the hydrogen production plant are located at the NPP site. The HES is also near the turbine system, but not necessarily within the turbine building, to reduce losses and minimize the amount of additional steam inventory that is cycled through the NPP. Two HES isolation valves are modeled in series (IV-1 and IV-2), mimicking the configuration of a typical MSIV arrangement. For the option in which superheated steam or a vapor-phase heat transfer fluid (HTF) is used in the TPD loop, the extraction heat exchangers comprise a two-stage system because there will be a phase change in both the hot and cold fluids.

The first heat exchanger HES-EHX-1 is a once-through steam generator (OSTG). The saturated steam is on the tube side of the heat exchanger, and the delivery steam is evaporated completely and superheated on the shell side. The reason for this design choice is the fact that the OSTG provides slightly superheated steam from a subcooled liquid inlet in a single heat exchanger. This combined with the vertical nature of the heat exchanger makes it reasonable for providing the desired heat transfer and fluid conditions. The

TPD loop is superheated by about 45°F if steam is used as the heat-transfer medium (vapor-phase HTF superheated temperatures would vary) to assist thermal delivery to the hydrogen plant approximately a kilometer away with minimal condensation.

TPD-EHX-2 has a design like a feedwater heater. The wet steam from the NPP enters the heat exchanger on the shell side to be condensed and subcooled by the condensate from the TPD loop. The condensate in the TPD loop is preheated in the tube side of the heat exchanger before being fully evaporated and superheated in HES-EHX-1. The subcooled liquid is designed to exit HES-EHX-2 at 193.3°C (380°F) at a high pressure of 68.3 bar (980 psi). This liquid is throttled to condenser pressures through an orifice. There is a check valve prior to the orifice which requires a high differential pressure to open. This valve ensures that the HES line remains pressurized in the event of a system malfunction to protect the chemistry of the nuclear steam in the case of a substantial tube leak in either of the extraction heat exchangers.

As the steam in the hydrogen production plant is pumped through the tubes of HES-EHX-2, it is preheated to saturation, then boils and superheats as it passes through the shell side of HES-EHX-1. The maximum flow rate of steam exiting the extraction heat exchangers and moving toward the hydrogen plant is 2.7×10^5 kg/hr (6.0×10^5 lb/hr) and the temperature is 252°C (485°F). This steam travels approximately 1 km to the hydrogen plant via a pipe equipped with steam traps to ensure dry steam is sent to the hydrogen plant's steam generator. The condensate is then pumped back to the HES heat exchangers, where it is boiled into steam again. Several valves in Figure 1 are highlighted in blue. This highlight indicates they are design options. A sensitivity analysis is conducted to weigh the safety benefits of these options and to inform the selection of the optimal configuration in terms of safety and cost.

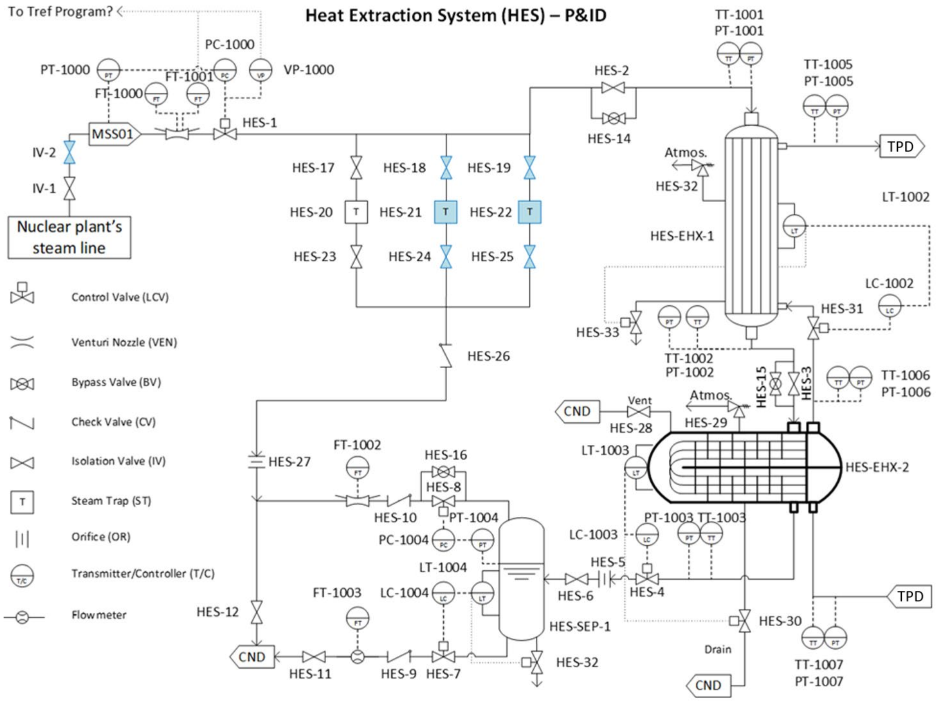

Figure 1. Piping and instrumentation diagram of two-phase to two-phase HES.

3. HAZARD ANALYSIS METHODOLOGY

3.1 Identification of Internal and External Events

Events modeled within a NPP PRA are divided between events internal to the NPP and those that are external to the NPP. External events are events that do not have a direct link to the structures, systems, and components (SSCs) of the NPP (e.g. natural hazards such as seismic events). The hazards considered for the addition of HES and HTEF potentially affect the frequency of internal and external events of the NPP. Jurisdictional boundaries were considered for licensing pathways. The NRC was found to have jurisdiction up to and including the site boundary [13]. Most events that can interfere with the operation and safety of the NPP affected by the location of the HTEF outside of the regulatory jurisdiction are treated as external events. The exception is the reactivity feedback that would occur if there were a sudden large leak in the TPD loop that services the HTEF. The internal event HTEF hazard analysis started on the secondary side of the heat exchanger after the delivery of thermal energy to the HTEF. External events were added to the NPP site by the potential for industrial interrupts and accidents at the HTEF. Other external events specific to the site are assumed to already be covered adequately by the existing NPP Level 1 PRA. The internal event hazard analysis within the NPP envelope concentrated on the potential for a large steam leak in the additional steam loop of the HES.

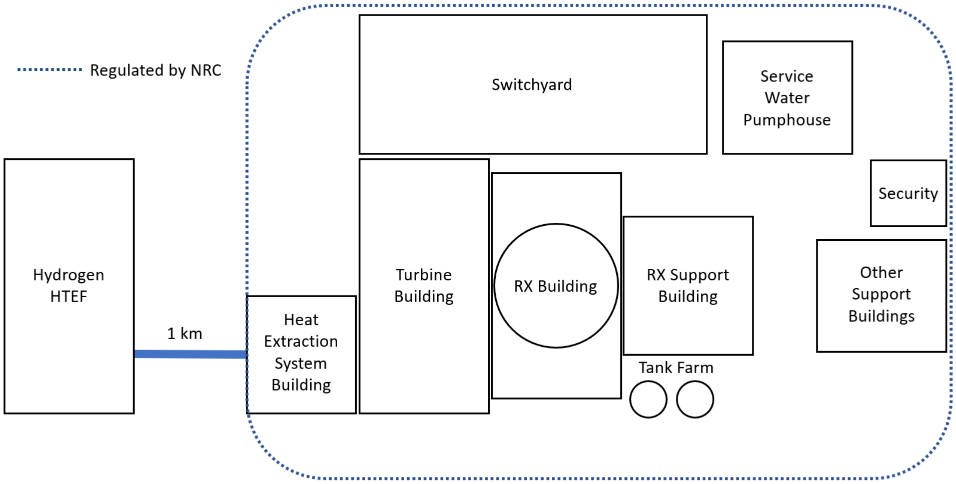

Figure 2. NRC jurisdictional boundary for LWR servicing an HTEF.

3.2 Design Options and Assumptions

The HES design options and assumptions considered for the representative NPP, HES, and HTEF are listed in the full PRA report [11]. Some key assumptions are that:

- HES isolation valves are in the same configuration as the NPP's MSIVs,
- Steam is the heating medium,
- Production hydrogen will be piped to a storage facility 5 km distant,
- Electrical power linkage between the NPP and HTEF will be through the grid to buffer direct upsets,
- The HTEF is 1 km distant from the nearest NPP critical structure,
- There is not a dedicated ceiling ventilation system in an enclosed HTEF building.

3.3 Identification of Nuclear Power Plant Safety-Critical Structures

The reactor building is a 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 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 local wind and seismic loads. These include refueling water storage tanks (RWST) and condensate storage tanks (CST).

The reactor building is identified as the initial critical structure. Reactor building concrete walls were characterized in [13]. 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 studies in references [9,10]. It is also adopted as the static pressure capability of nuclear concrete walls in the reference study for this paper as well, which summarizes reference [11].

Critical structures outside of the reactor building were identified when assessing high winds fragility for PRA. For most BWRs, these included 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 a RWST, an auxiliary or emergency feedwater tank, and/or 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 [15] was selected to act as a baseline for these fragilities. An updated high-wind fragility analysis was performed [16] which determined the mean fragilities of components commonly found in the switchyard. These wind pressure fragilities of 6-second gusts were transformed into blast overpressure impulse fragilities in SNL's hydrogen safety analysis performed in support of the PRA [17].

External water tanks are located close to the reactor building for use in providing 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 [15] 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 1. An overpressure event is a fraction-of-a-second impulse, so 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 [11,17].

Loss of switchyard components means a loss of offsite power (LOOP) event which 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 1.

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 tank, and hydrogen and nitrogen gas cylinders that present stored energy in the form of chilled and pressurized gas.

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

Table 1. Blast overpressure fragilities of NPP site components [17, 18].

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
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" [18].

3.4 NPP Hazard Analysis

The hazards associated with the addition of the HES to the existing NPP were considered through interviews with subject matter experts (SMEs), available design drawings, and options of the proposed HES. A Failure Modes and Effects Analysis (FMEA) was performed with a team that included SMEs with experience in PRA and reliability engineering, PWR operations, BWR operations, detailed design knowledge of the hydrogen HTEF proposed for this study, chemical, and controls experts. Information gathered from the SNL report [17] was used to determine the external events which could possibly affect the NPP. These included external overpressure events, heating medium (steam or HTF) leakage at the HTEF, and electrical power load loss from the HTEF.

An outline of the topics considered for the FMEA include:

- External overpressure event effects on NPP

- Thermal and electrical load effects on NPP
  - Thermal and Electrical load power profiles supplied by the NPP to the HTEF
- Hot standby mode
- Steam vs. HTF
- A list of the HTFs under consideration
- Placement of the HES
- Unique risks of BWR
- Unique risks of PWR
- Production hydrogen routing options and effects on risk.

The effects of possible external overpressure events on the NPP were summarized to include the damage to the containment, damage to external coolant storage tanks, 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 1-km distance were known prior to the performance of this FMEA. The team was therefore able to quantify a risk priority number (RPN) for each of the components considered based on the overpressure created from the MCA. 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 a following impulse might damage it, the fragility curves we use in this report are evaluated using the strongest possible first impulse and safety is assured where there is no structural 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. However, an accumulated hydrogen cloud detonation is not expected to cause another hydrogen cloud detonation because the facility is assumed to not have hydrogen storage.

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 hot standby mode discussion was centered around the thermal and electrical load effects. Differences were considered between steam and HTF in the secondary HES loop providing thermal energy to the HTEF. Steam was identified as the preferred heat-transfer medium from anecdotal evidence and discussion between the INL HTEF design team and PRA engineers with Electrical Power Research Institute (EPRI) BWR and PWR experts in January 2020. This preference is far and away due to familiarity of working with steam. There are benefits to using HTF in comparison to steam. The HTF maintains heat for a longer period of time, it can operate in a steady state or from a liquid to a vapor, therefore there is much less chance of cavitation of pumps, if used. Finally, the heat exchanger for a steam system would be larger and therefore more expensive than the heat exchangers for HTF.

The HES was 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 cost. The FMEA identified a safety benefit of placement of the HES within its own structure. Doing so removes the potential for an HES steam leak to cause damage to the turbine or safety buses.

Unique risks were considered for BWR and PWRs for each of the hazards identified. Also, hydrogen production and storage was discussed as a potential hazard. The current model consists of piping the hydrogen to a transfer facility at least 5 km away from the NPP. The transfer methods consist of truck transfer and other pipeline transfer, including the possibility of mixing with natural gas.

3.4.1 List of NPP Hazards Identified

The NPP FMEA results are summarized in Table 2. The FMEA RPNs were calculated, however, there was no RPN cutoff at which the hazard was not modeled in the PRA. Screening was performed on a hazard by hazard basis. All hazards identified are evaluated in the sections that follow. Those not screened by engineering evaluation are mapped into the respective event trees and the IE frequency for these event trees 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 location of the HTEF at 1-km distance.

The hazards either affected or added to the PRA by the addition of the HES and the HTEF are listed in Table 2. Also listed in the table is the event tree that the hazard would map to and the status (include or screen from the PRA) from the FMEA panel. There are five potential hazards considered in adding the HES and locating the HTEF at 1-km distance: 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 MSIVs, a heat exchanger leak in the HES, ignition of the heating medium, and the prompt loss of thermal load to the HES.

Table 2. FMEA potential failures from hazards and existing PRA event tree assignment.

Hazards	Potential NPP Process Functions Affected	Potential PRA Event Tree Assignment	FMEA Hazard Status
H_2 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 out if HES is not in the turbine building)
	Main (large) steam line rupture, unisolable steam leak	MSLB-HES	Included
HES heat exchanger 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 safety-related design basis event, but an economic risk. The risk to contaminate the HTEF heating loop is higher in BWR than in a PWR.	Screened out for Level-1 PRA. There is an economic and environmental concern.
Ignition of heating medium	Steam, non-flammable HTFs: flammable	None	Screened out for steam Not considered for HTFs
Prompt steam diversion loss, feedback	5% thermal diversion	None. NPP can handle 30% prompt load loss.	Screened out.

---

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

Hazards	Potential NPP Process Functions Affected	Potential PRA Event Tree Assignment	FMEA Hazard Status
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

3.5 HTEF Hydrogen Hazards Analysis

The risk associated with an HTEF in close proximity to an NPP, from which thermal and electrical energy are supplied, was evaluated for input into the PRA models. A facility component list was developed for a theoretical HTEF. Next, the associated leak frequencies for the individual components in the HTEF was evaluated to develop an overall facility leak frequency. The NPP site was evaluated for critical targets and the fragility of each was documented. Finally, the consequence of a hydrogen release and detonation in the HTEF was calculated and compared to the target fragility. Note that the consequence was evaluated at 1 km from the NPP, and a deterministic separation distance calculation was also performed [17].

The SNL hydrogen safety report [17], also presented at this Probabilistic Safety Assessment and Management conference (PSAM 16), details the leak frequency analysis. The leak frequencies per year were converted into a detonation frequency per year of operation. A bounding potential detonation-causing leak of a HTEF module production hydrogen pipe full flow break was determined to occur at a frequency of 5.2E-02/y (Table 3).

Table 3. HTEF System Frequency (yr^{-1})

Leak Size	HTEF System Frequency			
	Mean	**5th**	**Median**	**95th**
0.0001	2.28E+01	7.95E+00	1.70E+01	5.48E+01
0.001	4.19E+00	1.13E+00	3.32E+00	9.89E+00
0.01	1.37E+00	1.45E-01	7.47E-01	4.16E+00
0.1	1.33E-01	3.34E-02	1.01E-01	3.20E-01
1	5.19E-02	2.51E-03	2.18E-02	1.83E-01

3.5.1 Consequence of Detonation

Two types of potential detonations were identified: a high-pressure jet of hydrogen or an accumulated cloud of hydrogen. The high pressure hydrogen jet released from a pipe leak contains a detonable region within the strong concentration gradients created. Likewise, an accumulated cloud of hydrogen that doesn't ignite will have a region mixed with air that can detonate. Details of these analyses are in the SNL hydrogen safety report [17]. The bounding case of overpressure for both types of detonations at 1 km is shown in Table 4. The most susceptible component is the transmission tower in the switchyard with a 0.8 probability of failure at 0.2 psi.

Table 4: Consequence Results from Risk Analysis

Consequence	Bounding Overpressure at 1 km (psi)
Jet Ignition	0.06
Cloud Ignition	0.4

4. SUMMARY OF THE HAZARDS ANALYSIS

A detailed introduction of the need for a PRA and its components was presented. System descriptions and hazards were identified. The assumptions of the model were listed driven by hazards analysis, current knowledge of the HES and HTEF, and the generic nature of the model. Fragilities of 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 [18] includes the assessment of the hazards and the use of PRA to determine the effects on design basis accident IEs and CDF in support of licensing pathways for the proposed changes to the NPP. A summary of work and future research opportunities is also discussed.

5. ACKNOWLEDGEMENTS

This work is supported by and is performed in conjunction with the U.S. Department of Energy Office of Nuclear Energy Light Water Reactor Sustainability Program.

6. REFERENCES

[1] Nuclear Energy Institute, "Nuclear Costs in Context," October 2018

[2] M. Mueller, "Nuclear power is the most reliable energy source and it's not even close", U.S. Department of Energy, https://www.energy.gov, April 2020

[3] US Energy Information Administration, "Electricity in the United States", https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php, March 2020

[4] 10 CFR 50.59, "Changes, tests and experiments", U.S. Nuclear Regulatory Commission, https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0059.html, published August 29, 2017, accessed October 8, 2020

[5] RG-1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis", Revision 3, U.S. Nuclear Regulatory Commission, January 2018

[6] K. Wang, X. Zhang, Y. Miao, B. He, C. Wang, "Dispersion and behavior of hydrogen for the safety design of hydrogen production plant attached with nuclear power plant", International Journal of Hydrogen Energy vol. 45, Issue 39, pp 20250-20255, August 2020.

[7] J. Shi, B. Chang, F. Khan, Y. Chang, Y. Zhu, G. Chen, C. Zhang, "Stochastic explosion risk analysis of hydrogen production facilities", International Journal of Hydrogen Energy, Volume 45, Issue 24, Pages 13535-13550, May 2020.

[8] K. Groth, E. Hecht, J. Reynolds, M. Blaylock, and E. Carrier, "Methodology for Assessing the Safety of Hydrogen Systems: HyRAM 1.1 Technical Reference Manual," Sandia National Laboratories, SAND2017-2998, March 2017.

[9] INL/EXT-05-00137, "Separation Requirements for a Hydrogen Production Plant and High-Temperature Nuclear Reactor," September 2005.

[10] INL/EXT-19-55884, "Preliminary Probabilistic Risk Assessment of a Light Water Reactor Supplying Process Heat to a Hydrogen Production Plant," Revision 1, March 2020.

[11] INL/EXT 20 60104, “Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant”, October 2020.

[12] INL/EXT-20-58766, “Incorporation of Thermal Hydraulic Models for Thermal Power Dispatch into a PWR Power Plant Simulator,” Idaho National Laboratory, June 2020.

[13] INL/EXT-20-57762, “Establishing Jurisdictional Boundaries at Collocated Advanced-Reactor Facilities,” Idaho National Laboratory, August 2020.

[14] EGG-SSRE-9747, “Improved Estimates of Separation Distances to Prevent Unacceptable Damage to Nuclear Power Plant Structures from Hydrogen Detonation for Gaseous Hydrogen Storage,” Idaho National Environmental Engineering Laboratory, May 1994.

[15] IES Utilities Inc., “Duane Arnold Energy Center Individual Plant Examination of External Events,” NEI 05-01, November 1995.

[16] ARA-002672.03, “Vogtle Electric Generating Plant High Wind Hazard and Fragilities,” September 2016.

[17] SAND2020-7946, “Final Report on Hydrogen Plant Hazards and Risk Analysis Supporting Hydrogen Plant Siting near Nuclear Power Plants,” Sandia National Laboratories, New Mexico, July 2020.

[18] K. Vedros, R. Christian, A. Glover, C. Smith, “Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant – Part 2: Hazards Assessment and PRA Hazards Analysis”, Probabilistic Safety Assessment and Management Conference #16, June 2022