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Changing the World's Energy Future

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ABSTRACT

This paper presents recent updates made to the Level 1 probabilistic risk assessment (PRA) of light-water reactors (LWRs) coupled to a hydrogen production plant. It provides an overview of past PRA results collected from a pressurized-water reactor (PWR) and a boiling-water reactor (BWR) coupled to a 1150 MW high-temperature electrolysis facility (HTEF). It also gives the latest research results for a PWR and BWR coupled to a smaller 100 MW HTEF.

The differences between the two HTEF designs are listed, the key ones being the amount and quality of diverted LWR steam, the complexity of the heat extraction system (HES), and the electrical power source for the HTEF plant. A failure mode and effect analysis (FMEA) was conducted for the new HTEF design, and the LWR PRA models were modified to account for the newly identified risk contributors, including the steam loss event at the HES, the electrical overcurrent event at the HTEF and at the transmission line from the LWR plant, and the hydrogen detonation event at the HTEF.

Coupling LWRs to a 100 MW HTEF increases the frequencies of several initiating events. For the reference PWR, the largest frequency increase (i.e., 5.5%) was for the steam line break event. For the reference BWR, the largest frequency increase (i.e., 0.11%) was for the switchyard-related loss-of-offsite power (LOOP) event. The core damage frequency (CDF) increased by 6.56 and 0.03% for the PWR and BWR reference plants, respectively. These risk metrics were found to satisfy the safety criteria of both the 10 CFR 50.59 and RG 1.174 licensing pathways.

Keywords: PRA, LWR, hydrogen, HTEF

1. INTRODUCTION

The U.S. Department of Energy launched its Light Water Reactor Sustainability (LWRS) Program to maintain the continued operation of existing nuclear reactors in the United States, and to increase their economic competitiveness. One strategy investigated under this program is to implement flexible nuclear power plant (NPP) operations by devoting a portion of the heat they generate to the production of commercial hydrogen. While the decision to modify the NPP to supply thermal energy to external users is economic in nature, licensing of this modification is based on safety. The hazard analysis and risk assessment conducted for this modification—and which were previously covered in [1][2]—are summarized in this paper, which also analyzes a new potential design option.

The scope of this paper is a Level 1 probabilistic risk assessment (PRA) that models risk of core damage by quantifying the core damage frequency (CDF) associated with removing heat from the process steam

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generated by light-water reactors (LWRs). This value is then carried forward to calculate the risk of adding a hydrogen production plant that utilizes high-temperature electrolysis. Direct electrical coupling to the hydrogen plant is also modeled, enabling lower temperature electrolysis or boosting the temperature of the steam being delivered for high-temperature electrolysis. In the PRA, the high-temperature electrolysis facility (HTEF) electrically connected to the LWR is treated as both a potential internal and potential external event hazard inflicted on the LWR. The initiating event (IE) frequencies associated with adding the proposed LWR heat extraction system (HES) and HTEF are compared against the guidelines established in 10 CFR 50.59 [3], and the CDFs and large early release frequencies (LERFs) calculated from the PRA are compared against the guidelines established in RG 1.174 [4].

2. NPP MODIFICATIONS FOR HYDROGEN PRODUCTION

Two NPP system modifications are proposed. The first is to add the HES in order to extract thermal power for provision to the HTEF. The second is to add the switchyard components necessary to enable direct electrical coupling to the HTEF.

2.1. HES Design 1: Pre-turbine Steam Tap

Figure 1 shows a piping and instrumentation diagram of HES Design 1. The NPP steam line (main steam header) taps steam from the main steam line, downstream from the main steam isolation valves and before entering the high-pressure turbine. The steam available for extraction at the main steam header is saturated, with a total mass flow rate of 5.8×10^6 kg/hr (1.3×10^7 lb/hr) at 6.95 MPa (1,008.5 psia). The extraction heat exchangers required for transferring heat to the hydrogen production plant are located at the NPP site. The HES is also located near the turbine system (though not necessarily within the turbine building itself) so as to reduce thermal losses and minimize the amount of additional steam inventory cycled through the NPP.

The first heat exchanger, HES-EHX-1, is a once-through steam generator. The saturated steam is on the tube side of the heat exchanger; the delivery steam is fully evaporated, then superheated on the shell side. TPD-EHX-2 was designed in the manner of a feedwater heater. Wet steam from the NPP enters the heat exchanger on the shell side in order to be condensed and subcooled by the condensate from the thermal power delivery loop. The condensate in this 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) and a high pressure of 68.3 bar (980 psi). The maximum flow rate of the steam exiting the extraction heat exchangers and moving toward the hydrogen plant is 2.715×10^5 kg/hr (5.986×10^5 lb/hr) and the temperature of this steam is 252°C (485°F). In Figure 1, the valves highlighted in blue are presented as design options.

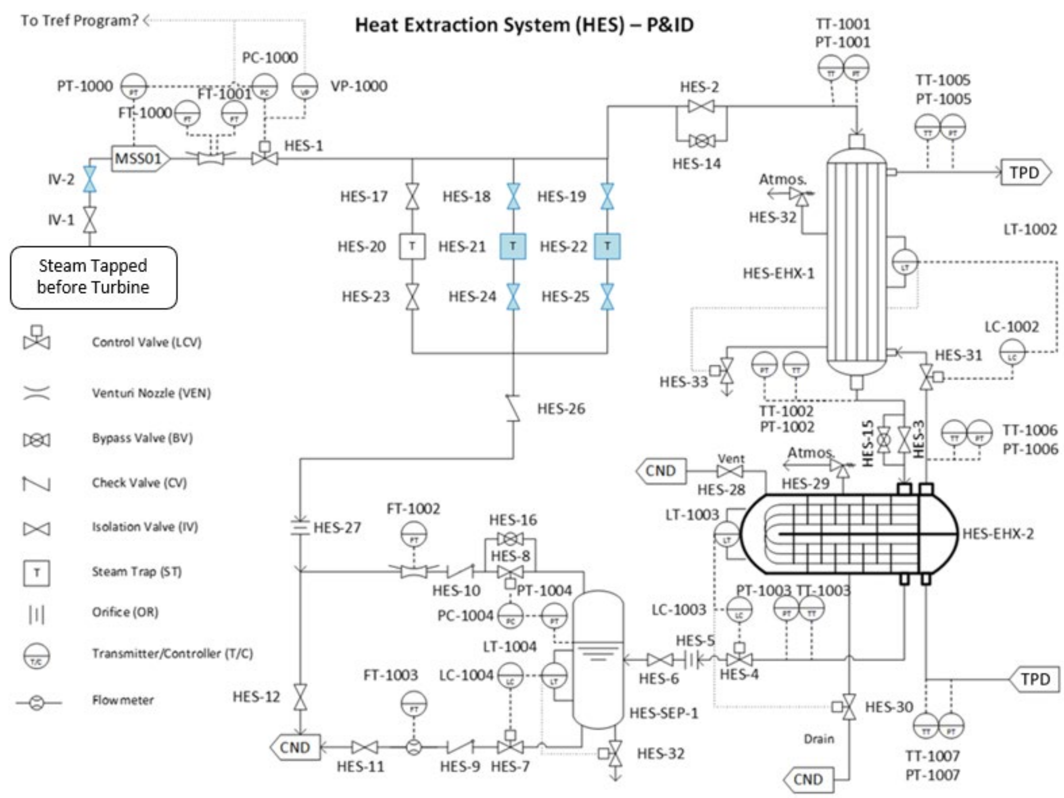


Figure 1. piping and instrumentation diagram of the pre-turbine steam tap design.

2.2. HES Design 2: Post-turbine Steam Tap

Figure 2 shows a conceptual diagram of a newer HES design [5]. The NPP steam line (main steam header) taps steam from the cold reheat line, downstream from the high-pressure turbine exhaust. The steam available for extraction at the main steam header is low-quality, with a total mass flow rate of 38,663 kg/hr (85,237 lb/hr) at 1.15 MPa (166.8 psi) and 186ºC (367ºF). This amount of steam reduces the total cold reheat flow going into the main steam reheater (MSR) by approximately 0.67%, and reduces the hot reheat flow going into the low-pressure turbines by about 0.76%. The steam extraction operation described above resembles a low-turbine bypass. This design is meant for extracting 25 MWt of steam. Of this 25 MWt of power, 20 is used to generate hydrogen, and the rest serves as a margin to offset any thermal losses. Other versions of this same design are aimed at extracting 80 and 100 MWt of steam.

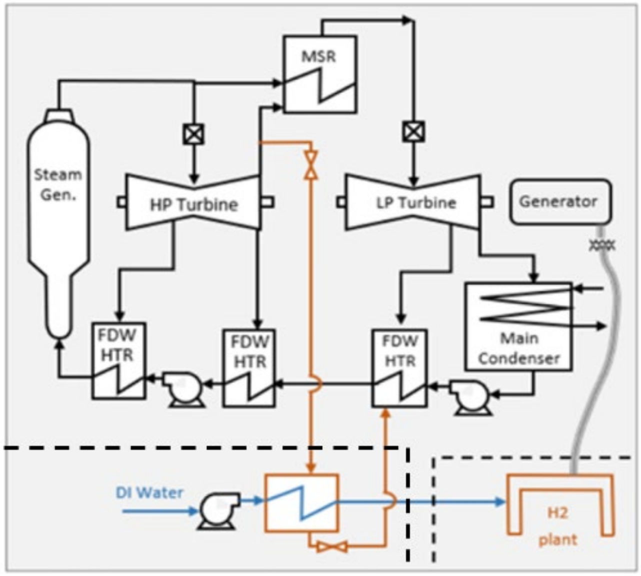


Figure 2. Conceptual diagram of the newly designed HES.

Figure 3 shows a diagram of the steam extraction line (downstream of the high-power turbines) leading to the reboiler. J1, J2, J5, and J6 are gate valves that are normally open during HES operation. J3 is a flow control valve with a constant pressure drop of 20 psig, and is assumed to have no flow-stopping capability. J4 is a stop-check 90-degree globe valve. The piping is located inside the turbine building.

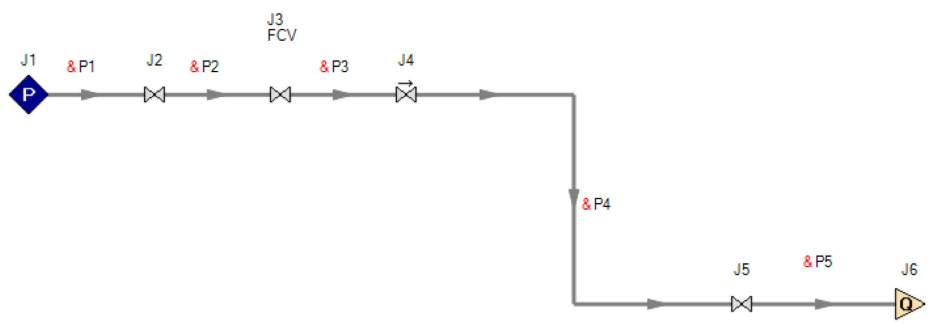


Figure 3. Diagram of the steam extraction line to the reboiler

2.3. Direct Electrical Connection

Figure 4 shows that the electrical connection to the HTEF extends from a tap just outside of the NPP main generator step-up transformer to the switchgear at the HTEF. The transmission line is a 0.5 km, 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. The new H2 power line has no effect on the switchyard voltage, breaker alignment, generator automatic voltage regulator (AVR) loading, or status of offsite power voltage-regulating devices. This eliminates the transmission line's impact on NPP safety systems that rely on offsite power.

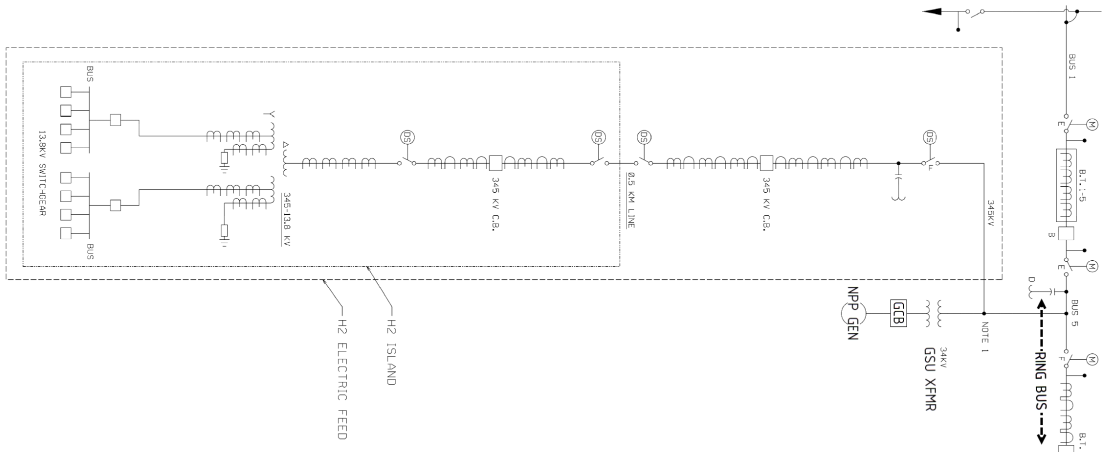


Figure 4. Transmission line and a portion of the ring bus switchyard arrangement at the NPP.

3. FMEA AND PRA MODELS

3.1. FMEA

A failure mode and effect analysis (FMEA) was conducted for the different HTEF designs—as applied to a pressurized-water reactor (PWR) and a boiling-water reactor (BWR). The topics considered in the FMEA included external overpressure event effects on NPPs, thermal and electrical load effects on NPPs, hot standby mode, HES placement, the unique risks of both BWRs and PWRs, and production hydrogen routing options and their effects on plant risk.

Some of the FMEA results were previously presented in [1][2]. Exhaustive FMEA tables pertaining to the various HTEF designs, including the new design, are available in [5]. Several hazards need to be quantified, including extraction steam piping failure, which can cause slight MSR power adjustments and increase the frequency of the steam line break initiator; high-pressure H2 jet combustion, which may cause switchyard component failures and increase the frequency of the loss-of-offsite power (LOOP) initiator; and unprotected overcurrent events at the HTEF direct electrical connection system, potentially increasing the frequency of the general transient initiator.

3.2. PRA Models

PRA models for the PWR and BWR equipped with HTEFs are given in [5]. The modeling strategy was to incorporate the FMEA-identified hazards into the existing PRA Level 1 risk initiators. The steam leak hazard was included in the total initiator frequency for steam line break, as reflected in Figure 5 and Figure 6.

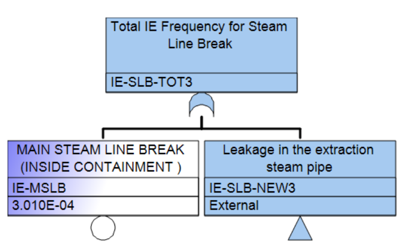


Figure 5. Steam line break initiator fault tree (FT).

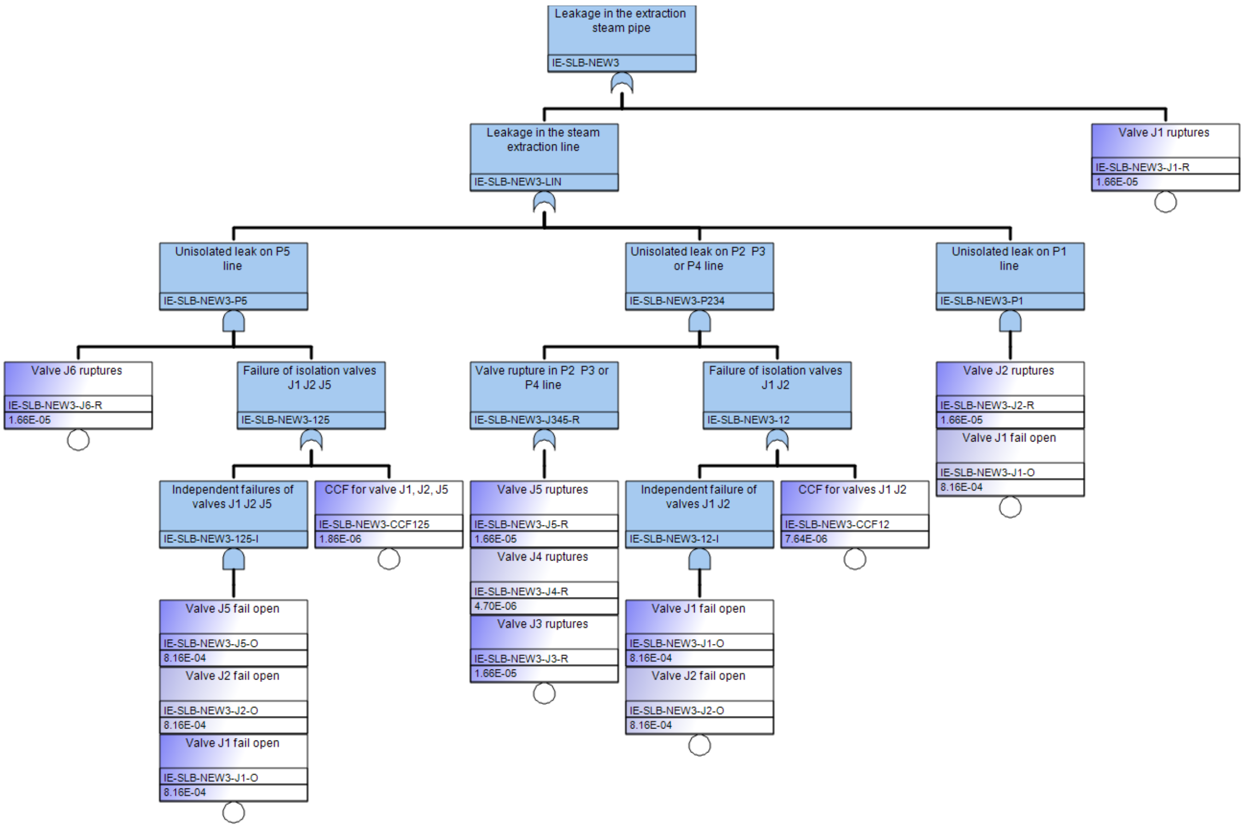
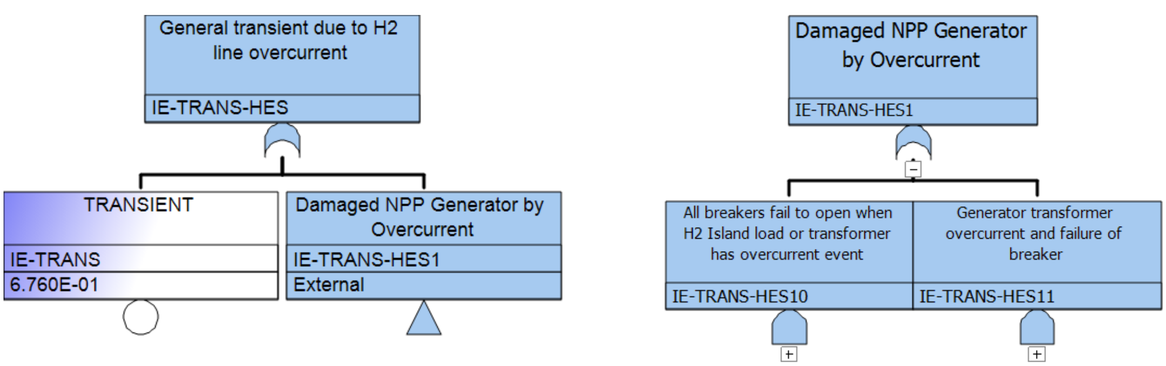


Figure 6. FT for a leakage of the steam extraction line in HES Design 2

Meanwhile, the overcurrent hazard due to the direct electrical connection was modeled into the general transient initiator shown in Figure 7.



(a) General transient initiator

(b) Damaged NPP generator fault tree

Figure 7. General transient initiator with the added risk of unprotected overcurrent at the HFEF's electrical connection.

The H2 detonation hazard is included in the LOOP initiator shown in Figure 8. This is because the switchyard components are most susceptible to the blast overpressure caused by H2 detonation. Therefore, the switchyard can be set as the bounding risk contributor in order to identify a safe site for the HTEF plant. Note that the fault tree in Figure 8 conservatively assumes the HTEF module to be enclosed within a container or building, which may trap leaked hydrogen and cause a cloud detonation after a period of 2 hours. This is the maximum credible accident event, which imparts a fragility value of 0.95 to the transmission tower located 1 km away. At this same distance, the fragility value imparted to the tower by high-pressure H2 jet combustion is 0. The switchyard failure probability (IE-LOOPSC-SC-JET-F and IE-LOOPSC-SC-CLOUD-F) are modifiable based on the distance between the H2 plant and the switchyard.

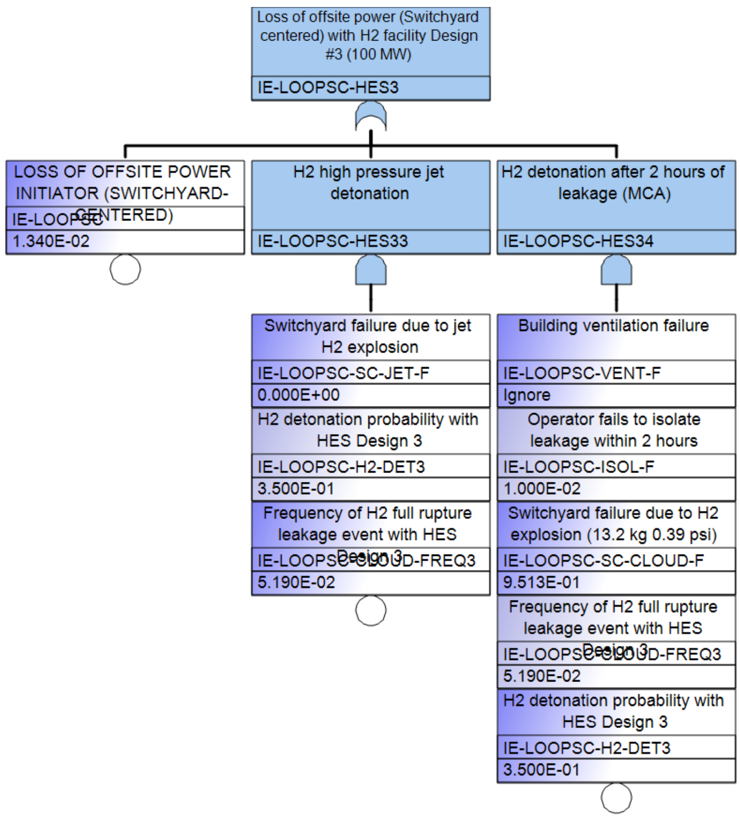


Figure 8. LOOP initiator with the added risk of the H2 detonation hazard.

4. RESULTS AND DISCUSSIONS

4.1. PRA Results

For a PWR equipped with HES Design 1, the highest initiator frequency increase is 5.5% (from the steam line break initiator), which results in a 4.9% increase in CDF. Meanwhile, for a BWR, the highest risk increase (from a switchyard-related LOOP) is 1.3%, which results in a 1.17% increase in CDF.

PRA results for the new HES design (i.e., the post-turbine steam tap design) are given in Table I and Table II for the PWR and BWR, respectively. The conclusion is similar to that reached for HES Design 1; namely, the highest risk contributors for PWRs and BWRs come from steam line break and LOOP events, respectively. The new hazard, the overcurrent event that results in a general transient, corresponds to a frequency of less than 1%.

Table I. Summary of PRA results for a PWR equipped with HES Design 2.

Risk metric	Case	IE Frequency (/y) (Δ%)	CDF (/y)	Cut Sets
Steam line break IE frequency with HES	Base assumptions	3.18E-4 **(+5.5%)**	—	10
Switchyard-related LOOP frequency with HES, conservative SPAR-H timing, without a dedicated ceiling ventilation system	Base assumptions	1.34E-2 **(+0.15%)**	—	2
General transient frequency with tap in switchyard to HTEF	Base assumptions	6.76E-1**(+0.00136%)**	—	9
CDF due to steam line break with HES	Base assumptions	—	2.68E-7 (**+5.55%**)	1955
CDF due to switchyard-related LOOP with HES, conservative SPAR-H timing, without a dedicated ceiling ventilation system	Base assumptions	—	2.76E-7 **(+0.22%)**	6192
CDF due to general transient with tap in switchyard to HTEF	Base assumptions	—	9.89E-7 **(<< 1.0%)**	2581

Table II. Summary of PRA results for a BWR equipped with HES Design 2.

Risk metric	Case	IE Frequency (/y) (Δ%)	CDF (/y)	Cut Sets
Steam line break IE frequency with HES	Base assumptions	1.66E-5 **(+0.002%)**	—	9
Switchyard-related LOOP frequency with HES, conservative SPAR-H timing, without a dedicated ceiling ventilation system	Base assumptions	1.34E-2 **(+0.11%)**	—	2
General transient frequency with tap in switchyard to HTEF	Base assumptions	7.40E-1 **(+0.00124%)**	—	9
CDF due to steam line break with HES	Base assumptions	—	8.00E-10 **(+0.02%)**	22
CDF due to switchyard-related LOOP with HES, conservative SPAR-H timing, without a dedicated ceiling ventilation system	Base assumptions	—	5.79E-7 (< **1%**)	5092
CDF due to general transient with tap in switchyard to HTEF	Base assumptions	—	3.90E-6 **(<<1.0%)**	5200

The final risk metric for the reference PWR and BWR plants when coupled to the HTEF is reported in Table III. It shows HES Design 2 to be slightly safer than HES Design 1.

Table III. Final risk metric.

Plant	Total CDF (/y)	Total LERF (/y)
PWR without HES	8.33E-6	8.04E-7
PWR with HES Design 1	8.88E-6 (+6.56%)	8.05E-7 (+0.12%)
PWR with HES Design 2	8.83E-6 (+6.00%)	8.04E-7 (+0.07%)
BWR without HES	2.84E-5	2.81E-5
BWR with HES Design 1	2.84E-5 (+0.03%)	2.81E-5 (+0.03%)
BWR with HES Design 2	2.84E-5 (+0.03%)	2.81E-5 (+0.03%)

4.2. Licensing Pathway

The pathway that utilizes an evaluation of the change in design basis accident (DBA) frequencies first uses 10 CFR 50.59 [3] to determine whether a license amendment request (LAR) would be required by 10 CFR 50.90 [6]. Changes that meet the 10 CFR 50.59 requirements do not require additional U.S. Nuclear Regulatory Commission review and approval. In a study commissioned by the LWRS Program [7], the effects that adding an HES had on PWR DBAs were evaluated for adherence to eight different criteria (e.g., that it produce an increase of less than 15% in the frequency of accidents already evaluated in the final safety analysis report. The PRA results given in the previous subsection suggest that the proposed modification meets the 10 CFR 50.59 criteria.

RG 1.174 [4] provides general guidance on analyzing the risk associated with proposed changes to plant designs and operations. Specifically, the thresholds and guidelines provided can be compared with the Level 1 PRA results for CDF and LERF. Under this guidance, the CDF should be below 1E-4, the change in overall CDF should be below 1E-5, the LERF should be below 1E-5, and the change in LERF should be below 1E-6. The PRA results in Table III suggest that the modification also successfully meets the RG 1.174 criteria.

5. CONCLUSION

Two generic PRAs were performed on adding a HES to LWRs: one for a PWR and one for a BWR. Two different HES designs, two sizes of HTEF (1,150 and 100 MWt), and a direct electrical connection from the NPP to the HES were modeled. The results reflect the applicability of the potential licensing approaches, which do not require a full U.S. Nuclear Regulatory Commission licensing review. The reference PRA models are generic. 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 5.6%. The PRA results for CDF and LERF support the use of RG 1.174 without necessitating a full LAR.

ACKNOWLEDGMENTS

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REFERENCES

1. K. Vedros, R. Christian, and A. Glover, "Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant – Part 1: Hazards Analysis," *Proceedings of Probabilistic Safety Assessment and Management (PSAM) 16*, Honolulu, Hawaii, June 2022.

2. K. Vedros, R. Christian, and A. Glover, "Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant – Part 2: Hazards Assessment and PRA," *Proceedings of Probabilistic Safety Assessment and Management (PSAM) 16*, Honolulu, Hawaii, June 2022.

3. Nuclear Regulatory Commission, "Changes, tests and experiments," 10 CFR 50.59, U.S. Nuclear Regulatory Commission. https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0059.html. Accessed October 8, 2020.

4. Nuclear Regulatory Commission, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis," Regulatory Guide 1.174, Revision 3. https://www.nrc.gov/docs/ML1731/ML17317A256.pdf.

5. K. Vedros, R. Christian, and C. M. Y. H. Otani, "Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High Temperature Electrolysis Hydrogen Production Plant," INL/EXT-20-60104 Rev. 001. Idaho National Laboratory, Idaho Falls, Idaho (2022).

6. Z. Ma, T. E. Wierman, and K. J. Kvarfordt, "Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants: 2020 Update," INL/EXT-21-65055, Idaho National Laboratory, Idaho Falls, Idaho https://doi.org/10.2172/1847110 (2021)

7. G. Swindlehurst, "Safety Evaluation of Modification for Process Steam Supply Capability in Pressurized Water Reactors, Rev. 1," GS Nuclear Consulting, LLC. Idaho National Laboratory, Idaho Falls, Idaho (2019).