Assessment of Hydrogen Plant Risks for Siting near Nuclear Power Plants

Austin Glover[a], Dusty Brooks[a], Austin Baird[a], and Kurt Vedros[b]
[a] Sandia National Laboratories, Albuquerque, United States
[b] Idaho National Laboratories, Idaho Falls, United States

Abstract: Understanding the safety risks of flexible nuclear power plant (NPP) operations to take advantage of excess thermal and electrical energy is critical. A promising option for NPPs to pursue is hydrogen production through high temperature electrolysis as an alternate revenue stream to remain economically viable. The intent of this study is to investigate the risk of a high temperature steam electrolysis hydrogen production facility (HTEF) in close proximity to an NPP for input into the plant probabilistic risk assessment (PRA). This analysis evaluates a postulated HTEF located 1 km from an NPP, including the likelihood of an accident and the associated consequence to critical NPP targets. This study shows that although the likelihood of a leak in an HTEF is not negligible, the consequence to critical NPP targets is not expected to lead to a failure of critical functionality at a distance of 1 km. Furthermore, the minimum separation distance of the HTEF is calculated based on the target fragility criteria of 1 psi defined in Regulatory Guide 1.91.

---

1. INTRODUCTION

Nuclear power plants (NPPs) may use flexible plant operations and generation to take advantage of excess thermal and electrical energy. However, NPPs must show that the operation of such a system is safe and does not pose a significant threat to the high consequence NPP facilities and structures. This is done through the plant probabilistic risk assessment (PRA). Hydrogen production through high temperature electrolysis is a feasible option for NPPs because the excess thermal and electrical energy produced through normal operation can be used to produce a carbon-free, storable energy source. When compared to the other methods of hydrogen production (such as steam methane reforming and low temperature electrolysis), high temperature electrolysis offers a more efficient and economically stable option. Steam methane reforming uses natural gas in the hydrogen production process, which introduces economic instability because of its reliance on natural gas, which experiences dramatic price fluctuations. Renewable energy such as wind turbines or solar photovoltaics can be used to create hydrogen through low temperature electrolysis with electrical energy only [1]. However, this method is less efficient when compared to high temperature electrolysis and is less economically attractive because thermal energy is less expensive than electrical energy [2]. NPPs can pursue hydrogen production through high temperature electrolysis as an alternate revenue stream to remain an economically viable power production option.

The intent of this study is to investigate the risk of a high temperature steam electrolysis hydrogen production facility (HTEF) in close proximity to an NPP, from which thermal and electrical energy are supplied. In this analysis, a theoretical HTEF located 1 km from an NPP will be analyzed in terms of risk to normal plant operations. 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 jet release 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.

2. BACKGROUND ON HIGH-TEMPERATURE STEAM ELECTROLYSIS

Water electrolysis is the process in which water is split into hydrogen and oxygen molecules through an electrochemical process. A typical system for water electrolysis includes an anode, cathode, electrolyte, and a power supply. The electrolyte can be constructed several ways: aqueous solution containing ions, a proton exchange membrane (PEM), or an oxygen ion exchange ceramic membrane. The system uses direct current, with the negative side on the cathode source, where hydrogen is produced. The anode side is connected to the positive side of the DC source [3]. High temperature steam electrolysis (HTSE) utilizes both heat and electricity to split water into hydrogen and oxygen in solid oxide electrolyzer cells (SOECs), which is essentially a solid oxide fuel cell operating in reverse [2]. This process splits water into oxygen and hydrogen by using steam at temperatures of ~600-850°C as well as electrical input. Note that although the ceramics used in the HTEF design require high temperatures to become ionically/electrically active, expensive catalysts (like platinum) that are used in PEM fuel cells/electrolyzers can be avoided. Preliminary general designs for an HTEF that utilizes excess steam and electricity from an NPP are described in the reports by Vedros and Otani [4] as well as Frick et al. [2]. Figure 1 shows an example high temperature electrolysis main process area flow diagram.

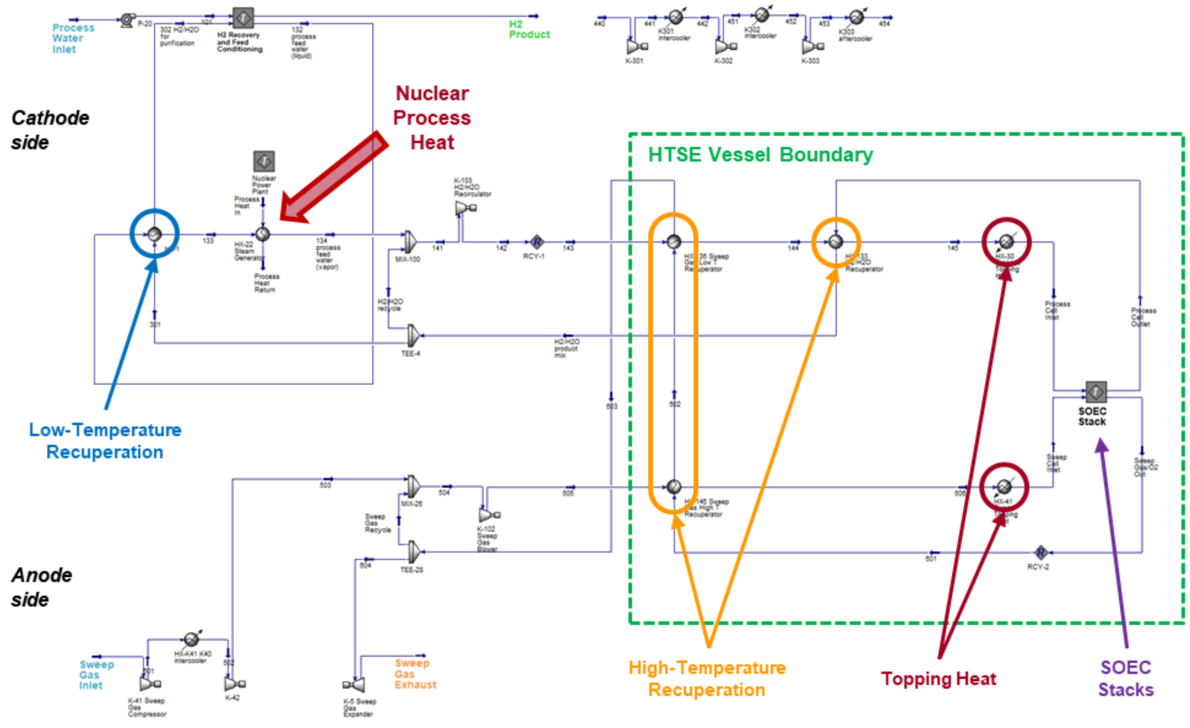

Figure 1: High Temperature Electrolysis Main Process Area Flow Diagram [2]

The two main systems of the HTEF design are summarized below [4].

1. Heat Extraction System: Heat is extracted from the NPP and delivered to a tertiary heat exchanger to generate steam that is then used for the electrolysis process.

2. HTEF: The HTEF is located 1 km from the walls of the pressurized water reactor (PWR) reactor building and the HTSE units are designed to produce a total of 300 US tons (272,156 kg) of hydrogen daily. Piping leads to a hydrogen storage facility 5 km away that contains 30 spherical tanks holding a total of 20 US tons (18,144 kg) of hydrogen [4].

3. HTEF ACCIDENT FREQUENCY

An important input into the plant PRA is the frequency at which an event is expected to occur. In this analysis, a preliminary design of a theoretical HTEF was evaluated to develop a component list of the system. Next, the frequency at which a hydrogen leak is expected to occur for a given component was calculated using a Bayesian statistical method. The system component list and component level leak frequencies were combined to define the system level leak frequencies for input into the PRA.

3.1. HTEF Component List

A preliminary design of a theoretical HTEF was evaluated to develop a component list for bottom-up leak frequency calculations. The component analysis focused on the HTEF and not the heat extraction system connected to the plant. The total component list was developed using piping and instrumentation diagrams (P&IDs), component cost analysis, and heat exchanger specification sheets [2]. Where specific information was not available, engineering judgement was used to develop assumptions for items such as pipe lengths and sizes. The preliminary design of the HTEF from Frick et al. [2] indicated that there are 46 different systems that are all fed from a common header and feed into a common header. The system is defined between those two sets of common headers. A summary of the components and their respective quantity is shown in Table 1.

Table 1: HTEF Component Quantity Summary

Component	**Quantity**
Compressor	92
Cylinder (Vessel, intercooler, Separator, Heat Exchanger)	874
Joint (Tee, Elbow, Reducer, Expander)	150
Pipe	7,360 m
Pump/Blower	276
Valve	966

3.2. Leak Frequency

To quantify the risk of an accident in an HTEF, it is necessary to establish the types of accidents that can occur. To do this, component leakage frequencies representative of hydrogen components must be determined as a function of the normalized leak size. Subsequently, the system characteristics (e.g., system pressure) will be used to calculate the consequence of the accident. Traditionally, industry data on component leakage events can be used to establish the leak frequencies. Unfortunately, there is little available data on hydrogen-specific component leakage events. Although major events are recorded in databases such as the DOE Hydrogen Incident Reporting database for lessons learned [5], the failure to record all events (e.g., small leakage events) and the number of operating hours represented in the database makes utilization of the data for analysis difficult. Previous risk evaluations have utilized published data on leakage events from non-hydrogen sources that are representative of hydrogen components [6].

Rather than selecting one value from generic sources, data from the different sources were collected and combined using a Bayesian statistical method. This approach has several major advantages for cases in which large amounts of data are not available. First, it allows for the generation of leakage rates for different amounts of leakage. Second, it generates uncertainty distributions for the leakage rates that can be propagated through the risk assessment models to establish the uncertainty in the risk results. Finally, it provides a means for incorporating limited hydrogen-specific leakage data with leakage frequencies from other sources to establish estimates for leakage rates for hydrogen components.

A Bayesian model was developed to predict the probability of a leak in various components used in an HTEF. The model was selected based on analysis of actual leakage data from the offshore oil industry. The model assumes that the mean leak frequency of any component is linearly related to the logarithm of the fractional flow area of the leak. The fractional flow area is the ratio of the leak area to the total flow area of the pipe. The HTEF system frequency was then calculated by summing each of the individual component frequencies for the entire facility. The quantity of components was multiplied by its associated leak frequency and was summed to calculate the system frequency. Table 2 shows the total HTEF system frequency as a function of break size. Note, that the median leak frequency indicates that a very small leak size (normalized leak area of 0.0001) is fairly common (~ 17 expected occurrences/yr). However, a full rupture (normalized leak area of 1) is expected to occur ~2 times every 100 years.

Table 2: 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

4. Consequence Evaluation

Another important input into the plant PRA is the extent of impact from a leak in the HTEF system. The important accident impact scenarios were defined through a hazard and operability analysis (HAZOP) [7]. Next, the fragility of high consequence targets at the NPP that may be impacted was addressed. Finally, the evaluation methodology to determine the parameter of interest (overpressure) for the consequence of a leak in the HTEF system was defined.

4.1. Accident Impact Scenarios

The different combinations of system variables in each system section were identified to determine the scenarios to be evaluated in this analysis. Table 3 gives details on the different pipe sizes for each temperature and pressure regime at various points along the hydrogen generation process. Each of these scenarios represent a unique evaluation case that will determine the worst-case full rupture break in each system.

Table 3: System Scenario Breakdown (as defined in [2])

Scenario	System Section	Temperature (°C)	Pressure (MPa)	Line Sizes (mm)
1	Mix-100 thru HX-KO1	735	0.52	203.2
2				254.0
3				300.0
4	HX-KO1 thru HX-KO2	75	0.48	152.4
5				203.2
6				254.0
7				300.0
8	HX-KO2 thru HX-KO3	75	1.01	88.9

Scenario	System Section	Temperature (°C)	Pressure (MPa)	Line Sizes (mm)
9				101.6
10				200.0
11				254.0
12	HX-KO3 thru K-301	25	2.23	88.9
13				200.0
14				254.0
15	K-301 thru System Output	50	7.00	200.0

4.2. Target Fragility

NPPs must show that the operation of an HTEF is safe and does not pose a significant threat to the high consequence NPP facilities and structures. An appropriate and conservative fragility criterion on which to evaluate the consequence of an explosive overpressure on NPP structures, systems and components is defined in Regulatory Guide 1.91 [7]. The incident overpressure below which critical targets of an NPP are expected to experience no significant damage is conservatively 1 psi [7]. Therefore, this criterion will be used to determine whether failure is expected to occur after exposure to overpressure from detonation of hydrogen leaked from the HTEF system.

4.3. Consequence of Detonation Methodology

The consequence of an accident in the HTEF system is an important parameter in the overall risk assessment. A leak in the system could release an unconfined high-pressure hydrogen jet with the potential to damage surrounding structures. The flammable jet released from the leak could result in a detonation, which would expose nearby targets to damaging overpressure. However, due to the strong concentration gradients in the hydrogen jet, the detonable region of the plume is reduced when compared to the total amount of fuel within the flammability range. Detonations are inherently unstable and depend on critical dimensions and the concentration gradient of the hydrogen jet, which determine if a propagating detonation wave can be supported. The limits of the hydrogen concentration in the jet to support detonation reduce the portion of the flammable plume that is available as fuel. The overpressure released through detonation of the large plume can be calculated from the detonable region, which is compared to the target fragility criteria to determine if critical damage occurs [8]. Note that this analysis does not account for possible natural and man-made barriers between the detonation area and the targets (i.e., the HTEF facility walls were not credited to reduce the overpressure at the critical NPP targets).

Initially, the concentration of hydrogen in the high-pressure jet must be calculated. To do this, the HyRAM software toolkit was used [9]. HyRAM provides a basis for conducting quantitative risk assessment and consequence modeling for hydrogen infrastructure and transportation systems. HyRAM has been designed to facilitate the use of state-of-the-art science and engineering models to conduct robust, repeatable assessments of hydrogen safety, hazards, and risk. With regard to calculation of the concentration of the high-pressure hydrogen jet, HyRAM incorporates computationally and experimentally validated models of various aspects of hydrogen release and flame physics.

The detonation cell size, λ, which is a measure of the scale of the instability of detonation, is used to characterize the detonation sensitivity of a given mixture [8]. The detonation cell size of a material depends on the mixture composition. The cell size defines the spacing between the transverse waves (the secondary waves that propagate perpendicular to the direction of detonation propagation) and is integral in determining whether a detonation will propagate or not. Detonations are more likely to initiate and propagate when the mixture has a small cell size (i.e., there is a tighter spacing of transverse waves). Smaller cell sizes are a result of faster chemical reactions and typically require less energy to begin the detonation or transition from deflagration to detonation [8]. However, in application, a high-pressure hydrogen release will result in a plume with non-uniform fuel distribution. The gradient of the detonation cell size also limits the ability of a detonation to propagate through a mixture. Work in this area has shown that detonation waves will fail to propagate if the cell size increases by more than ~10% across a single cell length [8]. Therefore, in this application, detonation propagation is only considered in regions for which $d\lambda/dx < 0.1$. To determine whether the cell size is small enough to support detonation, the thickness of the flammable mixture for the region in which $d\lambda/dx < 0.1$ is evaluated to see how many detonation cells can fit within the layer. According to the critical layer height criterion, a threshold of at least 5 cells within the layer is used to define the detonable region of the hydrogen mixture [8].

Detonation of the hydrogen jet release can result in significant overpressures. The overpressure was estimated with a model informed by experimental studies of large-scale hydrogen jet releases that were ignited [8].

5. CONSEQUENCE RESULTS AT 1 KM AWAY FROM NPP

The overpressure from ignition of a hydrogen leak in the HTEF was evaluated for a location 1 km away from the NPP. Calculations were performed for two ignition scenarios: ignition of the high-pressure jet and ignition of an accumulated cloud of hydrogen. Note that both of these scenarios were evaluated deterministically using full break diameters of the piping (i.e., no partial breaks were considered). Therefore, the frequency associated with these breaks equate to the 1.0 normalized leak size from Table 2.

5.1. High Pressure Jet

Each of the scenarios in Table 3 have been evaluated using the methodology discussed in Section 4.3. A Python script was written to perform all of the necessary calculations and determine the overpressure at 1 km away from the accident. The detailed results of Scenario 15, including the plume concentration, cell size, cell size gradient, and detonable region (Figure 2), and overpressure as a function of distance (Figure 3) are shown below. Note that Scenario 15 is a 200.0 mm break with a temperature of 50°C and pressure of 7.0 MPa

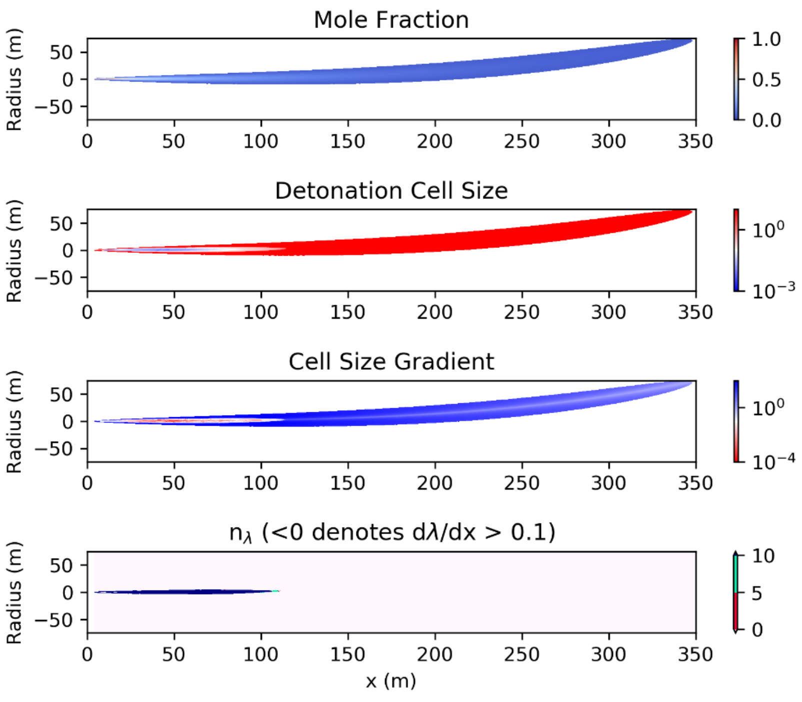

Figure 2: Scenario 15 Jet Plume Consequence Evaluation Results [10]

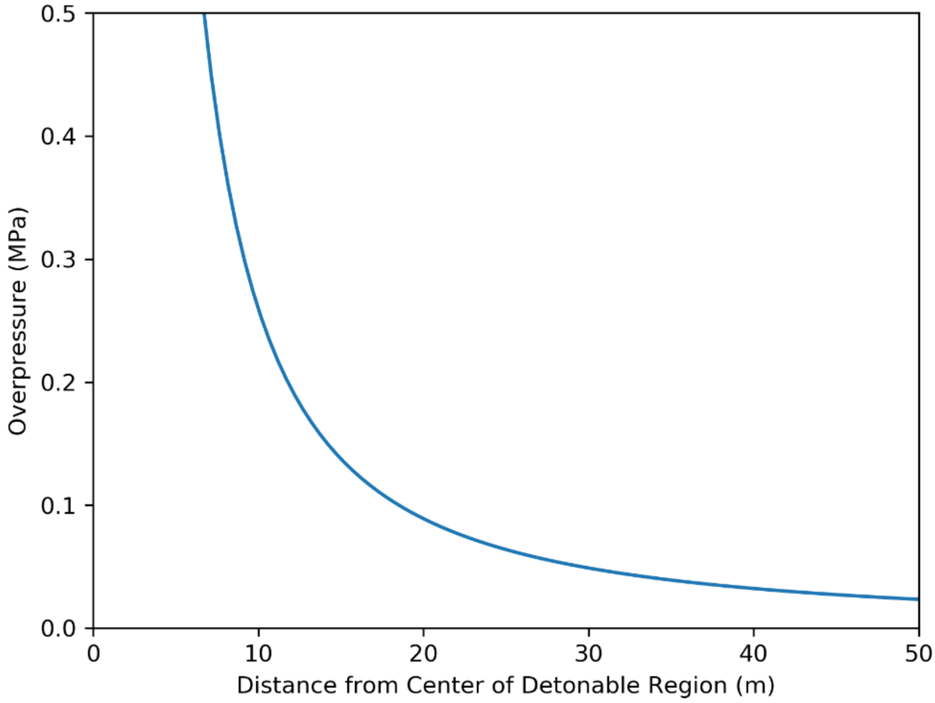

Figure 3: Scenario 15 Overpressure Evaluation Results [10]

Table 4 shows the summary overpressure results at 1 km away from the accident location. As shown in the table, the largest impulse overpressure at a distance of 1 km away is ~400 Pa (0.06 psi), which is well below the 1 psi fragility failure criterion. Therefore, the fragility of the critical targets at an NPP would not be compromised at a distance of 1 km away from the high-pressure jet break scenarios.

Table 4: Overpressure Results for Worst-case High Pressure Jet Scenarios

Scenario	Overpressure at 1 km	
	(MPa)	(psi)
1	3.03E-05	0.00440
2	4.37E-05	0.00633
3	5.69E-05	0.00826
4	2.90E-05	0.00420
5	4.68E-05	0.00679
6	6.70E-05	0.00972
7	8.76E-05	0.0127
8	2.16E-05	0.00313
9	2.70E-05	0.00392
10	8.13E-05	0.0118
11	11.9E-05	0.0173
12	4.52E-05	0.00656
13	16.4E-05	0.0238
14	24.0E-05	0.0349
15	38.4E-05	0.0557

5.2. Hydrogen Accumulation Scenario

An alternate consequence of a hydrogen leak in the HTEF system is ignition of an accumulated cloud of a hydrogen/air mixture. If ignition of the high-pressure hydrogen jet does not occur immediately after the hydrogen release, the hydrogen can accumulate and mix with ambient air before being ignited. The total quantity of hydrogen released in this case would contribute to the overpressure experienced by the critical NPP structures. The amount of hydrogen released is a function of the system flowrate at the leak location as well as the time to leak isolation. Table 5 shows the two largest flowrates in the HTEF system [11], along with assumed leak times and the total hydrogen quantity that would be released. Note, that the isolation times were assumed to range between 5 minutes and 120 minutes, which span the assumed range of operator response times to isolate the hydrogen leak. As shown, due to the low flowrates, the total mass of hydrogen released is fairly limited. Also, 100% of the released quantity is treated as hydrogen, even though the actual concentration of hydrogen is less than 100%. Similar to the high-pressure jet release detonation calculations, the hydrogen is assumed to be well mixed in air and the heat of combustion value of 119 MJ/kg is used to calculate the overall energy. A 100% yield (i.e., the fraction of available combustion energy participating in blast wave generation) was assumed for the overall energy calculation as well.

Table 5: Total Quantity of Hydrogen Released for Varying Flowrates and Isolation Time

System	Flowrate (nlpm)	Isolation Time (min)	Total Hydrogen Quantity (kg)
Hydrogen Product, 93% H_2	750	5	0.3
		10	0.7
		20	1.3
		30	2.0
		60	4.0
		120	8.1
Hydrogen Product Manifold to Condenser, 62% H_2	1,223	5	0.5
		10	1.1
		20	2.2
		30	3.3
		60	6.6
		120	13.2

Due to this variability, a range of released quantities will be evaluated. The overpressure can be calculated as a function of distance from the accident location. In this case, the entire quantity of released hydrogen will be considered as the detonable region. The energy from the released hydrogen is calculated and input into the overpressure calculation using the same overpressure calculation methodology documented for the jet plume cases. Figure 4 shows the total energy and overpressure at a distance of 1 km from the accident as a function of total amount of leaked hydrogen. As shown, the overpressure experienced at 1 km is ~ 0.7 psi for the case that estimates 50 kg of hydrogen released. When compared to the fragility criterion of 1 psi for the static pressure capacity, there is more than a 40% margin. In this analysis, it was assumed that the maximum credible accident (MCA) is denoted by a postulated isolation time of 120 minutes. Note, that even for the MCA, the maximum quantity of hydrogen released is ~13 kg (~0.4 psi overpressure). Therefore, the overpressure generated by the release of 50 kg of hydrogen is a conservative comparison case. Similar to the comparison made in the overpressure from detonation of a high-pressure hydrogen jet, the critical targets would not be compromised at a distance of 1 km.

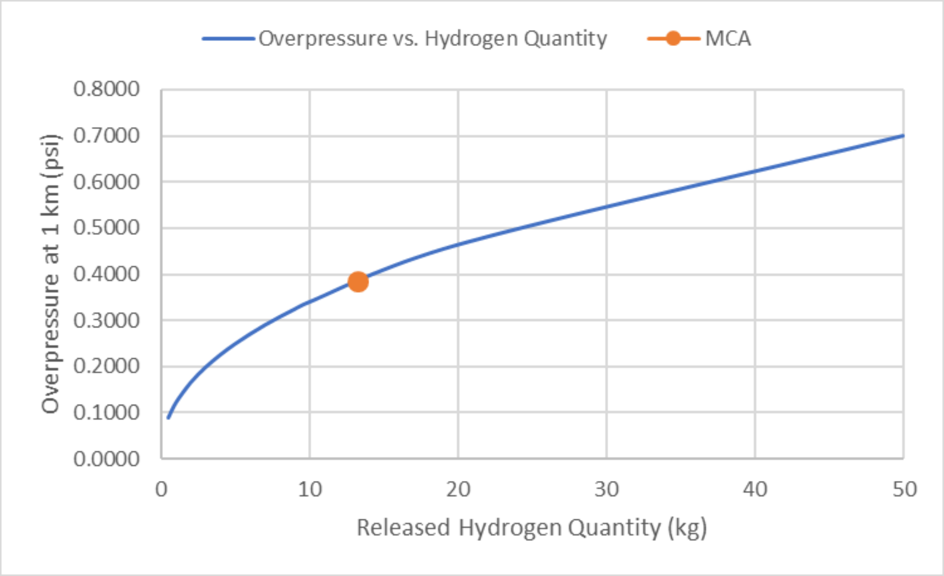

Figure 4: Overpressure as a Function of Hydrogen Quantity in Cloud

6. MINIMUM SEPARATION DISTANCE RESULTS

The minimum separation distance at which the overpressure from ignition of a hydrogen leak in the HTEF reached the 1 psi fragility criteria was also evaluated. Similar to the 1 km distance evaluation, calculations were performed for two ignition scenarios: ignition of the high-pressure jet and ignition of an accumulated cloud of hydrogen.

6.1. High Pressure Jet

Each of the scenarios in Table 3 have been evaluated using the consequence of detonation methodology. A Python script was written to perform all of the necessary calculations and determine the minimum separation distance at which the overpressure value reached 1 psi. The overpressure as a function of distance from the center of the detonable region for Scenario 15 is shown in Figure 5. Note that Scenario 15 is a 200.0 mm break with a temperature of 50°C and pressure of 7.0 MPa

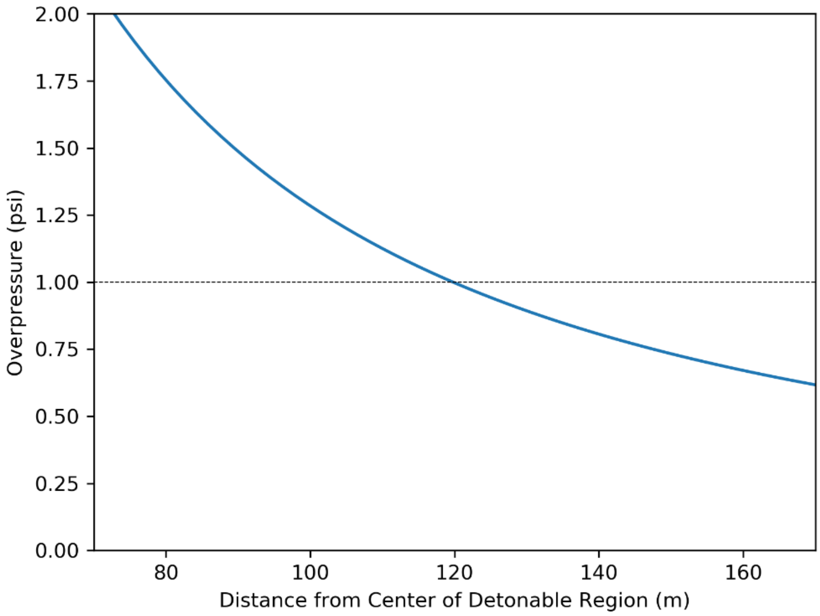

Figure 5: Scenario 15 Separation Distance Results

Table 6 shows the separation distance for each of the different scenarios. As shown in the table, the largest separation distance is ~120 meters away from the NPP. Note, that this is in comparison to the 1 psi fragility failure criterion, which was deemed to be conservative. Therefore, a factor of safety was not addressed in these calculations.

Table 6: Minimum Separation Distance for High-Pressure Jet Cases

Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Separation Distance (m)	18	23.7	28.9	17.4	24.9	32.6	39.8	14	16.5	37.7	50.1	24.3	63.6	84.5	120

6.2. Hydrogen Accumulation Scenario

Each of the scenarios in Table 5 have been evaluated for the minimum separation distance as well. The overpressure as a function of distance from the center of the detonable region for the 13.2 kg hydrogen release case is shown in Figure 6.

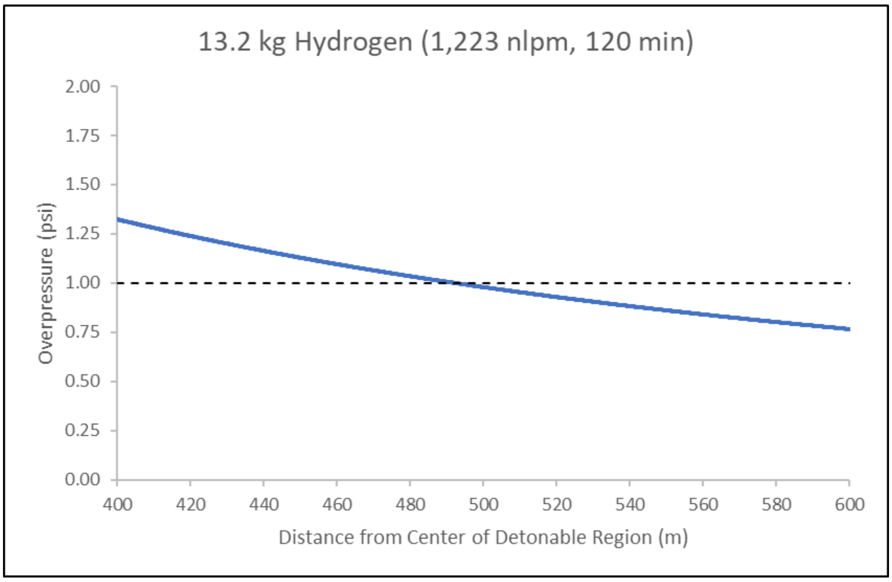

Figure 6: 13.2 kg Hydrogen Release Separation Distance Results

Table 7 shows the separation distance for each of the different scenarios. As shown in the table, the largest separation distance is ~492.1 meters away from the NPP. Note, that this is in comparison to the 1 psi fragility failure criterion, which was deemed to be conservative. Also note that it was assumed that the escaped gas was 100% hydrogen, which effects the total energy and resulting overpressure of the blast.

Table 7: Separation Distance for Hydrogen Accumulation Scenarios

System	Flowrate (nlpm)	Isolation Time (min)	Total Hydrogen Quantity (kg)	Separation Distance (m)
Hydrogen Product, 93% H2	750	5	0.3	139.4
		10	0.7	184.9
		20	1.3	227.2
		30	2.0	262.3
		60	4.0	330.5
		120	8.1	418.2
Hydrogen Product Manifold to Condenser, 62% H2	1,223	5	0.5	165.2
		10	1.1	214.9
		20	2.2	270.8
		30	3.3	310.0
		60	6.6	390.6
		120	13.2	492.1

7. CONCLUSION

The risk of an HTEF located near an NPP has been evaluated, including the likelihood of an accident and the consequence. The frequency was developed with a bottom-up approach by documenting the components in an HTEF and calculating the cumulative frequency contribution from each component. The frequency of a leak in the evaluated HTEF system is fairly high (~17 expected occurrences/year for a very small leak and ~2 expected occurrences every 100 years for a full rupture, although there is much uncertainty in these estimates). This is because there are 46 modular units that increase the number of components, which increases the likelihood of a leak. Although the frequency of a leak in an HTEF is not negligible, the consequence of a detonation does not detrimentally affect critical targets at the NPP at a distance of 1 km. A full rupture leak was evaluated at different locations in the HTEF system with varying line sizes and system pressures. Also, the consequence of detonation of the high-pressure jet release of hydrogen and the detonation of accumulated hydrogen were evaluated as worst-case scenarios. The largest overpressure seen at a distance of 1 km away from the accident location was ~0.06 psi for detonation of the high-pressure hydrogen jet and ~0.4 psi for detonation of the MCA accumulated hydrogen cloud. This does not challenge the fragility criteria of the critical targets. Note, that consequences for leak sizes smaller than full rupture were not evaluated because the full rupture consequences (worst-case) did not challenge the fragility criteria. Therefore, failure due to a smaller leak size would not be expected to occur. The minimum separation distance was calculated for all of the worst-case scenarios as well. The largest minimum separation distance was 120 m for the high-pressure hydrogen jet and 492 m for the MCA accumulated hydrogen cloud. Both of these separation distances show the opportunity to safely decrease the 1 km assumed distance from the NPP.

References

[1] J.P. Py and A. Capitaine, “Hydrogen Production by High Temperature Electrolysis,” Areva/EDF.

[2] INL, “Techno-economic Analysis of Hydrogen Generation for the "REDACTED" Generating Station,” Idaho National Laboratories, Idaho Falls, 2019.

[3] Y. Naimi and A. Antar, “Hydrogen Generation by Water Electrolysis,” 22 08 2018. [Online]. Available: https://www.intechopen.com/books/advances-in-hydrogen-generation-technologies/hydrogen-generation-by-water-electrolysis. [Accessed 13 02 2020].

[4] K. Vedros and C. Otani, “Preliminary Probabilistic Risk Assessment of a Light Water Reactor Supplying Process Heat to a Hydrogen Production Plant,” Idaho National Laboratories INL/EXT-19-55884, Idaho Falls, 2019.

[5] “DOE Hydrogen Incident Reporting Database,” [Online]. Available: http://www.h2incidents.org/.

[6] J. LaChance, W. Houf, B. Middleton and L. Fluer, “Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards,” Sandia National Laboratories, SAND2009-0874, March 2009.

[7] U.S. Nuclear Regulatory Commission, “Regulatory Guide 1.91: Evaluations of Explosions Postulated to Occur at Nearby Facilities and on Transportation Routes near Nuclear Power Plants,” April 2013.

[8] C. Bauwens and S. Dorofeev, “Quantifying the Potential Consequences of a Detonation in a Hydrogen Jet Release”.

[9] 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.

[10] A. Glover, D. Brooks and A. Baird, “SAND2020-10828: Final Report on Hydrogen Plant Hazards and Risk Analysis Supporting Hydrogen Plant Siting near Nuclear Power Plants,” October 2020.

[11] INL, “System Design Description: 150 kW SOEC System,” September 30, 2019.

[12] M. Kaneshige and J. Shepherd, “Detonation Database,” GALCIT Technical Report FM97, [Online]. Available: http://shepherd.caltech.edu/detn_db/html/db.html. [Accessed February 2020].