Hydrogen: Facility Siting and Risk Analysis

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Previously, we have discussed the importance of managing hydrogen safety hazards through Process Hazard Analysis (PHA) and understanding damage mechanisms on materials and equipment that are exposed to hydrogen. This paper will cover another aspect of hydrogen safety, from the perspective of consequence modeling and risk management.

Hydrogen electrolyzer facilities and liquefaction infrastructure pose unique safety challenges compared to traditional gasoline production. This does not mean that hydrogen as fuel is "riskier" than other fuels, but rather that a focus on safe handling and operation is key to developing this infrastructure safely and successfully. Facility Siting Studies (FSSs) and Quantitative Risk Assessments (QRAs) are powerful tools used to quantitatively assess consequences and risks from credible loss of containment scenarios resulting in explosion, fire, or toxic events, to onsite personnel and/or offsite population. Such assessments are used to objectively evaluate the hazards present within hydrogen facilities and to provide guidance and prioritization methods for mitigation measures that will be most effective in reducing onsite and offsite consequences and risks to tolerable levels.

There are many components to a QRA, some of which involve sophisticated modeling and computational techniques that are continually evolving. To ensure QRAs are accurate, consistent, and understandable, industry and regulators need to align on technology and methods for performing these assessments. This white paper discusses the importance of risk assessments and also provides an example of a hydrogen facility risk assessment, and how it can be utilized to achieve societal goals of a less carbon-intense energy infrastructure while also maintaining a safe work environment.

The Challenge

To assess the issues that arise in successfully applying QRA methodology, an overview of the key steps and considerations involved in a QRA is provided on the left side of this paper.

Key QRA Considerations:

Hazard Evaluation

- **Credible event selection**
- **Release locations and discharge/dispersion modeling**
- **Jet fire/pool fire thermal radiation calculations**
- **VCE blast wave calculations**
- **Pressure vessel burst blast wave calculations**

Consequence Modeling

- **Flammable/Thermal impacts to personnel**
- **Toxic impacts to personnel**
- **Blast wave impacts to structures and their occupants**
- **Blast wave impacts to outdoor populations**

Risk Analysis

- **Initiating event frequency**
- **Probability of ignition and ignition timing**
- **Probability of meteorological conditions**

Risk Discussion

- **Individual risk**
- **Societal risk**
- **Onsite vs. offsite risk (as applicable)**
- **Comparison to tolerance criteria**
- **Evaluation of risk mitigation strategies, where needed**

Multiple variations in approach exist among different QRA providers, in both the methodology and software applied, as well as the final presentation of the results obtained. Additionally, there is imperfect knowledge about the physical phenomena taking place during a release event (the **consequence side** of the risk equation). There is even uncertainty associated with equipment failure rates and conditional outcome frequency factors such as ignition probabilities (the **frequency side** of the risk equation). Historical data sources vary widely in some cases, particularly with respect to ignition probability, and may exhibit inherent biases (i.e., be influenced by the analyst's personal experience).

Thus, left completely to their own devices, the results from one practitioner to the next can be expected to show significant variability. This is not a fatal objection for using QRA methodologies, as potential uncertainties and inconsistencies can be managed. Ultimately, moderate inconsistencies do not significantly affect the decisions that result from an analysis. The Center for Chemical Process Safety (CCPS) has published books[1,2], authored by BakerRisk, detailing methods for consequence and risk modeling for process facilities. Some overseas regulators have also published detailed methodologies, such as the TNO colored books[3], which can be applied. Therefore, results from a QRA can provide guidance and information that can be used for rational and objective decision-making. However, given the unique features of hydrogen, some degree of fundamental alignment on basic technical knowledge is necessary to reduce such variability to an acceptable level.

Managing Uncertainties

Stakeholders (companies, industry groups, and overseas regulators) employ various approaches to managing this array of uncertainties and inconsistencies. One example of this is the National Fire Protection Association (NFPA) which publishes standards and codes that are adopted by local governments to minimize the effects and risks of fire. NFPA 2 has published a standard focused specifically on safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed and cryogenic liquid form in hydrogen facilities and provides prescriptive-based and performance-based compliance options. The performance-based compliance option defines specific design scenarios for evaluation and the authority having jurisdiction (AHJ) approves methodologies and parameters associated with the evaluation[4].

In a risk assessment, these sources of inconsistency can be organized by those who affect the consequences of an event and the resulting risk incurred on the facility. Each of these is explored next.

Consequence Modeling

For a loss of containment event, the steady state rate of release is generally well-understood and described by accepted algorithms. For transient releases, greater complexity is involved in the analysis. Methods can vary significantly after the point of release, however, and the methods are ever-changing and improving. Some industry groups such as the Center for Chemical Process Safety (CCPS) within the American Institute of Chemical Engineers (AIChE) have published books detailing the leading dispersion models. Even so, there are several tuning parameters within these models that still lead to differences between practitioners.

Some government bodies provide recommended guidelines and methodologies to conduct QRA. The U.S. Environmental Protection Agency (EPA) has Risk Management Program (RMP) tools that can provide a conservative consequence of a release. However, it should be noted that RMP only provide guidance in estimating consequence impact, and not the risk incurred on the facility. Other countries, such as Saudi Arabia for example, dictate which computational methods to use in conducting a facility siting. Other countries such as Singapore depend instead on an approved list of QRA providers[5], which includes BakerRisk, who have been vetted to ensure demonstrated competency in the QRA field. Some of the major QRA practitioners control their own models' accuracy by checking their model results against actual field tests and prior industrial incidents. Some, including BakerRisk, have their own test facilities that are used to validate consequence analysis results.

The considerations above apply to consequence assessments of all flammable and toxic materials; however, hydrogen has unique behaviors. Having a very low molecular weight, hydrogen is often handled at either high pressure or cryogenic conditions, which may challenge some consequence models. It is also generally understood that hydrogen produces higher-velocity flame fronts compared to almost any other flammable gas, aggravating the potential for a cloud ignition to result in a detonation.

There is a common misconception that an outdoor hydrogen release will not result in a vapor cloud explosion (VCE) due to the buoyancy of the gas. However, many studies and field experiments have proved that this is not always the case[6]. Furthermore, there have been at least 14 known hydrogen incidents where the gas cloud release resulted in a VCE without confinement[7]. Previous BakerRisk field experiments[8] show that lean hydrogen-air mixture clouds as low as 16% may result in deflagration to detonation transition (DDT) if congestion exists. What is sometimes less understood is that, in contrast to almost all other flammable materials, the energy involved in a hydrogen explosion can include parts of the cloud that are not inside a congested volume[9]. The lack of industry-wide understanding of this phenomenon means that many risk analysts may underestimate the magnitude of a potential hydrogen detonation.

Risk Calculations

The frequency of a specific event outcome consists of a number of subcomponents, including the following:

1. Frequency of the initiating event (failure rates).
2. Probability and timing of ignition, and strength of ignition sources (for flammable releases).
3. Probability of given meteorological conditions (wind direction, atmospheric stability, etc.).

There is still developing and varying information related to initiating event frequency and probability and timing of ignition. Historically, there have been extensive variations among failure rate sources, as information from the chemical process industry was not available and the primary data sources were: (a) expert opinion, (b) nuclear-industry, and (c) offshore oil/gas industry. Among the experienced QRA providers who have devoted resources to exploring this issue, the differences have narrowed greatly. However, hydrogen has a limited historical record and as such, failure rates from other cryogenic industrial applications are typically used to supplement hydrogen-specific data. Therefore, greater uncertainty than usual can be expected for some period of time, and a robust data collection infrastructure should be developed globally to support the industry.

Two identical facilities will not be operated, inspected, or maintained identically, so differences in failure rates should also be expected between the two. One facility might choose to incorporate, for example, the effects of safety standards at its site, while another relies on active or passive mitigation for its analysis. Each is relevant, but also open to the potential for biases and inconsistent application. Lastly, there are operational differences between facility types that might call for thoughtful consideration – for example, the effect of using cryogenic vs. high-pressure storage.

Ignition probability prediction has its own difficulties. Unlike dispersion models, it may not be practical to conduct realistic field experiments at the facility scale. Real-life ignition probability data has been collected but is very susceptible to 'data bias' – for example, potential under-reporting of flammable releases that did not ignite or that had minor impacts because of conditions specific to that event. In the case of hydrogen specifically, subject matter experts have widely varying views on its ignitability in real-life conditions. Detailed reports on this subject have been prepared and adopted in a CCPS book[10], authored by BakerRisk. Like other QRA variables, ignition probability may seem like an arcane subject, but the risk value from flammable events is directly proportional to this probability, which is entirely relevant.

Wind and weather release direction probability is generally the easiest to estimate and commonly involves obtaining data from the nearest airport that collects detailed meteorological information. The methods used among the experienced QRA practitioners regarding meteorology data do not vary greatly. Risk calculations may also include additional conditional probabilities such as release orientation, time slot, event duration, and success/failure of protection devices, if evaluated.

Managing Differences in Risk Methods and Results

Short of prescribing exact methods and software for evaluating all aspects of a hydrogen QRA, there will be differences between the results and presentation of results provided from one practitioner to the next. In general, QRAs provide risk results that draw similar conclusions and lead to similar actions in response. Regardless of the methods and software used to perform a hydrogen QRA, the study should be fully supported by research and development and validated against testing and previous incidents. Some variation among QRA service providers should not drive industry or regulators to create an overly prescriptive set of study requirements.

Modeling Methodology

The case study shown in this paper follows BakerRisk QRA methodology utilizing SafeSite$_{3G}$$^{©}$ and QRATool$^{©}$ software tools for consequence and risk calculations, respectively. Figure 1 describes highlights and major steps involved in BakerRisk's approach to QRA methodology. While some variations are expected, results should generally be similar to other industry-known methodology and tools. Note that this QRA methodology is not specific to hydrogen and is applied in risk assessments of fire, toxic and explosion hazards.

Case Study

To illustrate the QRA methodology applied to a hydrogen facility, this paper will discuss a hypothetical hydrogen electrolyzer and liquification facility as a case study. Because this model does not represent an actual facility, the study should be interpreted as an example of how to assess potential hazards that can be expected in a hydrogen facility. Results from this hypothetical case study should not be applied directly to a hydrogen facility, as consequence and risk results vary by layout, location, surroundings, building design, occupancy, etc.

Figure 2 presents an overview of the example facility including areas of congestion/confinement along with the locations of release sources, buildings, and ignition sources. Five work groups are expected to be present during normal operation of this facility, namely Admin, Engineer, Lead Operator, Operators, and Truck Driver. The distribution of time each work group spends onsite in buildings and outdoor areas was used to derive average occupancy during day hours and night/weekend hours, which is shown in Table 1 and Table 2.

Table 3 provides a summary of release sources modeled in the hydrogen electrolyzer and liquification facility. The process was segmented into different release sources that define a portion of the process similar to node divisions in a PHA, and a release source is modeled assuming the most severe conditions within each relevant process section.

Release scenarios were selected by reviewing process information such as process flow diagrams (PFDs) and heat and material balances (H&MBs) to define a representative set of hazard sources.

- A range of release sizes (0.5-inch, 2-inch, and full-bore rupture up to 6-inch) was considered for each identified hazard source.

Dispersion of the material from releases was modeled taking into account thermodynamic properties, flashing, rainout, pooling, evaporation, and gas dispersion.

- Flammable impacts were assessed for “open” and “closed” buildings.
- Vulnerabilities were predicted for each toxic scenario as personnel evacuate or shelter-in-place (SIP) using dose calculations and probit expressions and can credit mitigations such as HVAC isolation and PPE.

Jet and pool fire consequences were assessed using industry appropriate fire models.

- Vulnerabilities were predicted for each fire scenario as personnel evacuate or shelter-in-place (SIP) using dose calculations and probit expressions.

Vapor cloud explosions were modeled using the Baker-Strehlow-Tang (BST) methodology to determine blast loads on buildings. Building damage levels were predicted for each onsite building using dynamic Single-Degree-of-Freedom (SDOF) analysis of structural components.

- Vulnerability values were predicted for each onsite building for each blast scenario assessed based on the building construction

Converted vulnerabilities to risk results.

- Vulnerabilities were converted to predicted number of fatalities based on occupancy data for each location (building/outdoor area).
- Release frequencies were estimated based on pipe length/size, type/number of equipment, and failure rates based on industry experience.
- Scenario frequency was calculated by multiplying the release frequency by probabilities for weather conditions, release/wind direction, ignition timing, and the time of day.
- Frequency and consequence results were combined to define risk for each scenario and the overall risk was calculated by adding the risk of each scenario assessed.

Figure 1. BakerRisk QRA Methodology

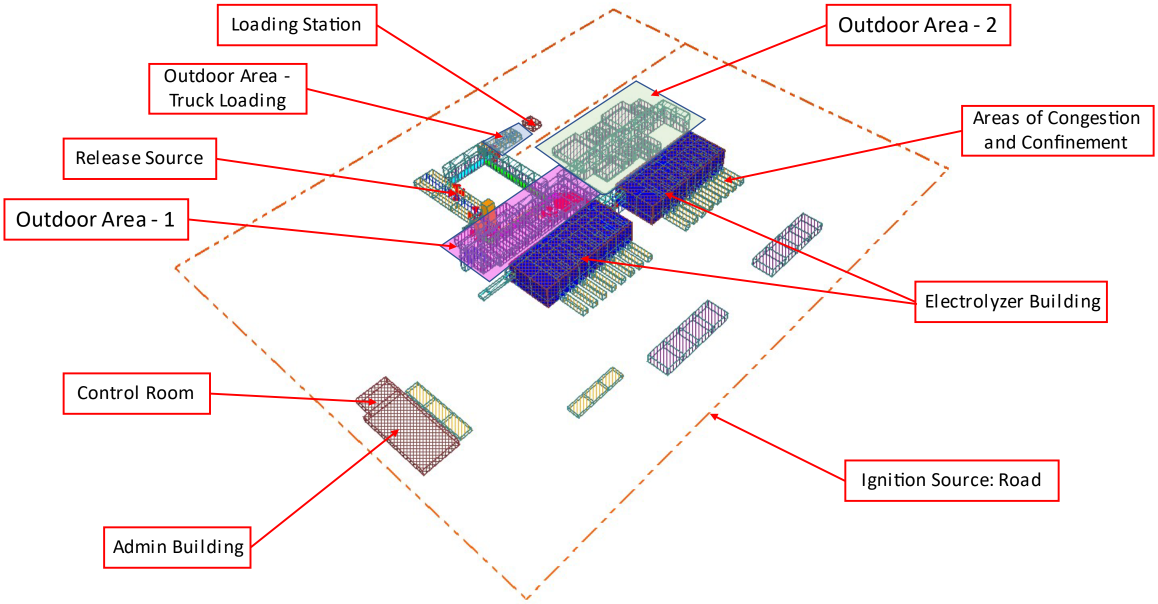

Figure 2. Case 1 Model

Table 1. Buildings Construction Type and Occupancy

Building	Construction Type	Day Occupancy	Night/Weekend Occupancy
Admin Building	Pre-engineered metal framed construction building	5	0
Control Room	Pre-engineered metal framed construction building	2	2
Electrolyzer Building 01	Pre-engineered metal framed construction building	0	0
Electrolyzer Building 02	Pre-engineered metal framed construction building	0	0
Loading Station	Connex structure with metal roof truss	1	0

Table 2. Outdoor Area Population

Outdoor Area	Day Occupancy	Night/Weekend Occupancy
Area – 1	0.1	0.1
Area – 2	0.1	0.1
Area – Truck Loading	4	0

Table 3. Release Sources Modeled

Source	Description
H2Unit-01-ElectrolyzerOutput	Hydrogen and water output from an electrolyzer
H2Unit-02-ElectrolyzerOutput	Hydrogen and water output from an electrolyzer
H2Unit-03-H2Separator	Overheads from hydrogen/water separator
H2Unit-04-H2Separator	Overheads from hydrogen/water separator
H2Unit-05-FeedtoPSA	Feed knockout before PSA system
H2Unit-06-PSADryers	PSA Dryers
H2Unit-07-PSAOutput	Output from PSA dryer unit
H2Unit-08-RegenCompressor	Regeneration compressor for PSA dryer unit
H2Unit-09-CoolingExchanger	Discharge from Cooling exchangers to Liquefaction exchangers
H2Unit-10-LiquefactionExchanger	Discharge from Liquefaction exchangers to hydrogen storage tanks
H2Unit-11-H2Storage	Hydrogen storage tank
H2Unit-12-H2StorageVaporizers	Hydrogen storage tank pressure vaporizer
H2Unit-13-H2StorageOvhd	Hydrogen storage tank vapors
H2Unit-14-H2ExchangersA	Hydrogen gas through heat exchangers
H2Unit-15-H2ExchangersB	Hydrogen gas through heat exchangers
H2Unit-16-H2Compressor	Hydrogen gas compressor
H2Unit-17-H2GasAdsorber	Hydrogen gas adsorber to Liquefaction unit
H2Unit-18-Loading	LH2 Loading Scenario
PIPE-01-GH2_FROM_ELEC_TO_PSA	Pipe: Gaseous hydrogen from electrolyzer to PSA
PIPE-02-GH2_FROM_PSA_TO_COOLING	Pipe: Gaseous hydrogen from PSA to cooling
PIPE-03-LH2_FROM_COOLING_TO_STORAGE	Pipe: Liquid hydrogen from cooling to storage
PIPE-04-GH2_FROM_STORAGE_TO_COOLING	Pipe: Gaseous hydrogen from storage to cooling
PIPE-05-GH2_FROM_COOLING_TO_COMP	Pipe: Gaseous hydrogen from cooling to compressor
PIPE-06-LH2_FROM_STORAGE_TO_LOADING	Pipe: Liquid hydrogen from storage to loading
PIPE-07-GH2_FROM_LOADING_TO_PROCESS	Pipe: Gaseous hydrogen from loading to process

Case Study Results

Contours plots were generated to provide consequence results for full bore releases (i.e., up to 6-inches). Each release case was rotated in 16 directions, with the results for all release cases and directions combined to form a composite contour. Figure 3 shows the flammable gas concentration contours to the endpoints of the ½ of the lower flammability limit (LFL), the LFL, and the upper flammability limit (UFL). Figure 4 provides thermal radiation contours to endpoints of 4, 12.5, and 37.5 kW/m^2. Figure 5 shows the side-on overpressure contours for all blast scenarios assessed including traditional deflagration-to-detonation (DDT) scenarios (blast energy limited to the flammable cloud within congestion), to thresholds of 0.6, 0.9, 3, 5, and 10 psig. Note that although unlikely, it is possible in these DDT scenarios for flammable gases outside of congestion to be involved in the DDT, resulting in a more energetic explosion. These scenarios are accounted for in risk calculations.

Table 4 and Table 5 summarize the societal risk results of this case study in terms of locations incurring the greatest risk and sources contributing the greatest risk at the facility, respectively. Table 6 shows the individual risk incurred by each worker at the facility. Risk results should be compared to company or industry risk tolerance criteria to determine whether results are considered tolerable, broadly acceptable, or intolerable. Tolerance criteria can help to determine if further actions or mitigations will be required, should be sought to determine practicality (safety benefit versus cost), or will not be required[11].

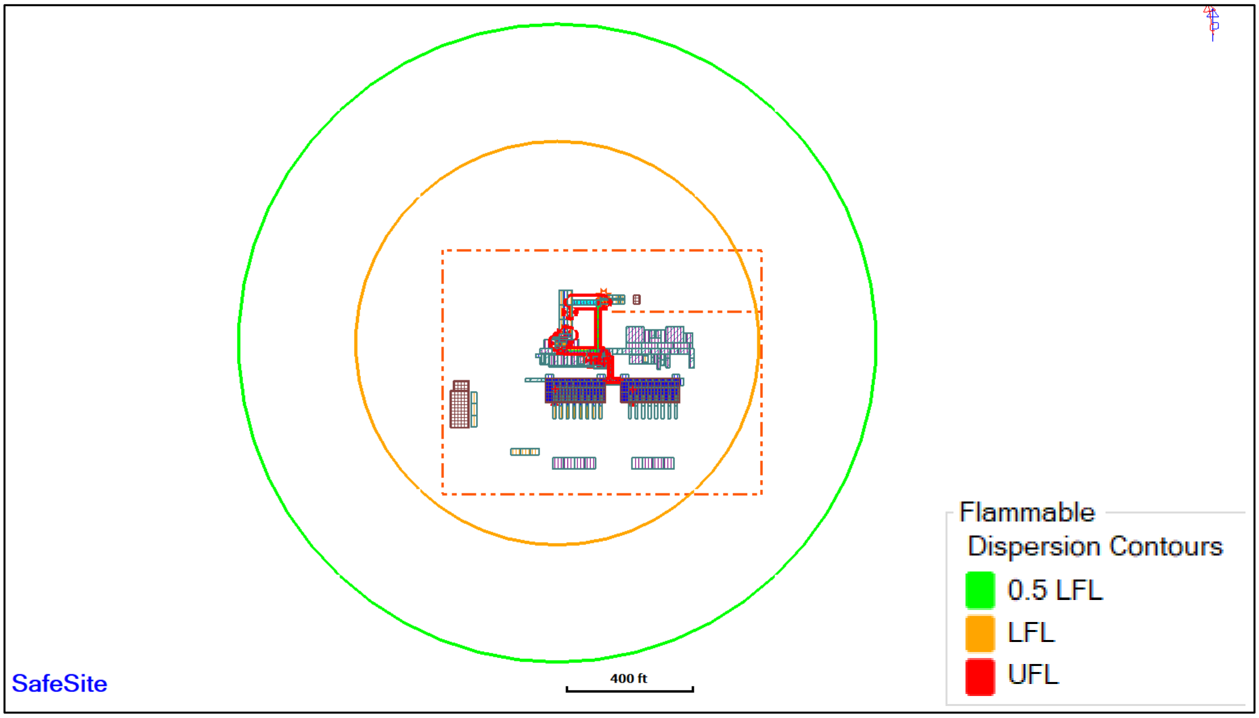

Figure 3. Flammable Dispersion Contours for Full-Bore releases up to 6"

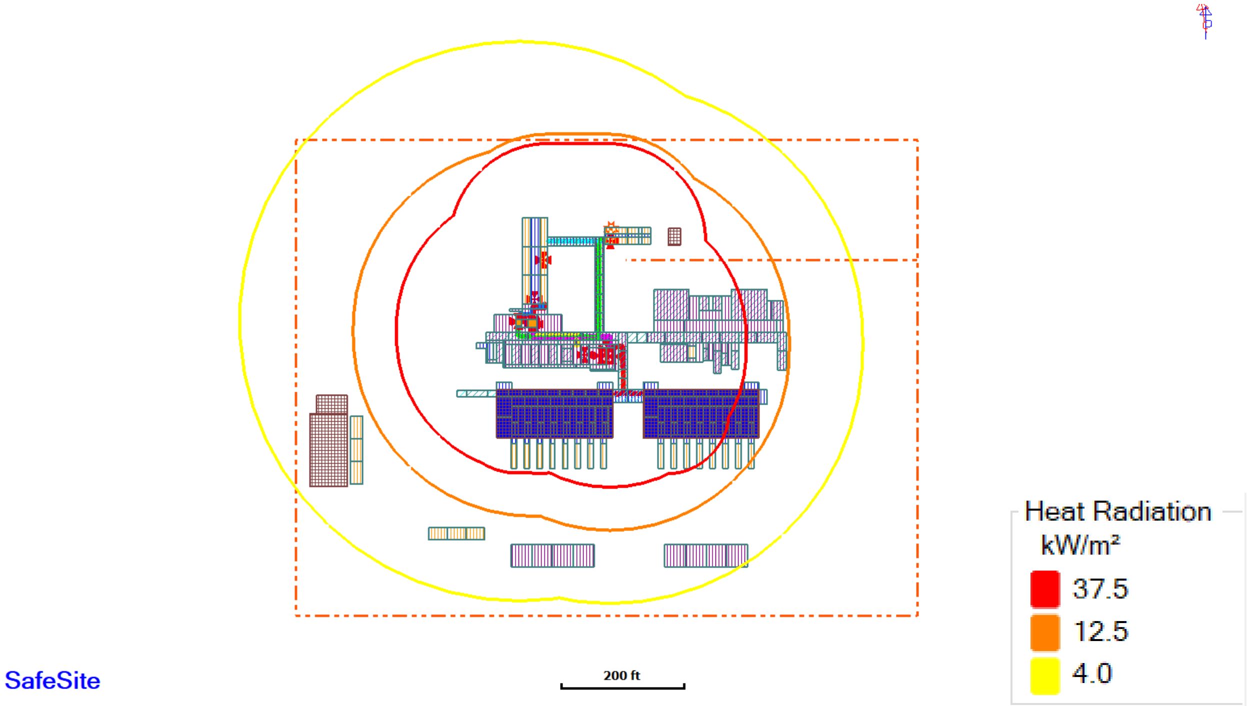

Figure 4. Thermal Radiation Contours for Full-Bore releases up to 6”

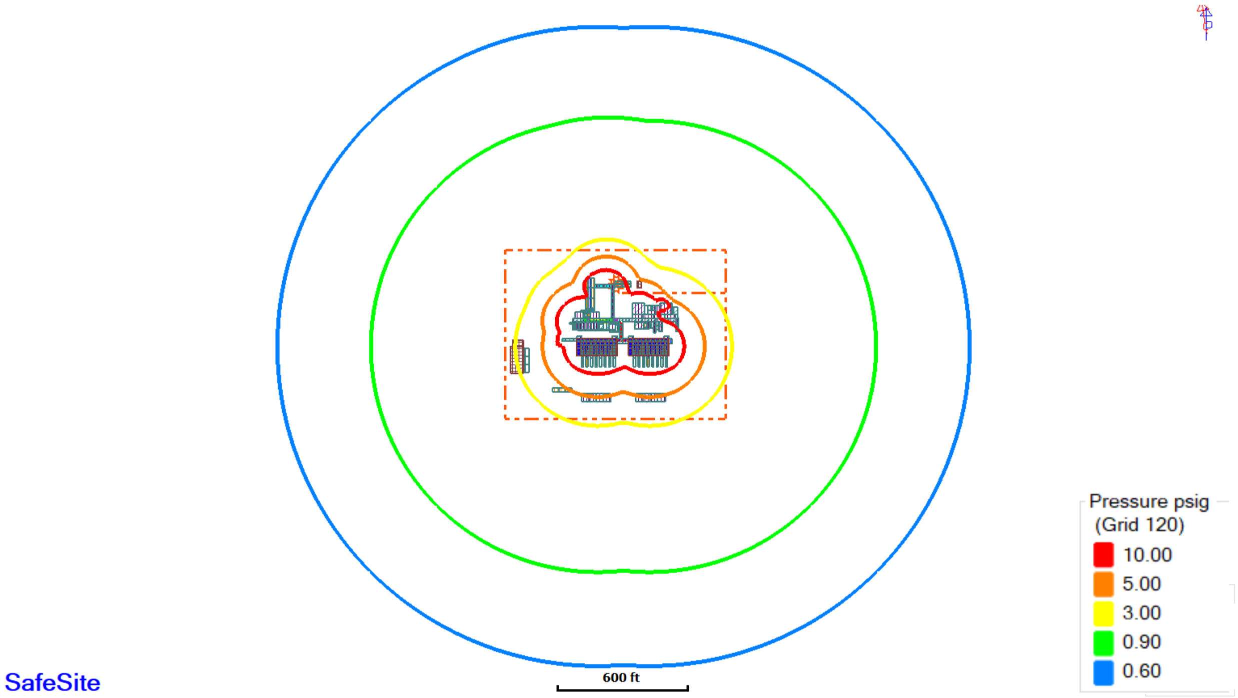

Figure 5. Overpressure Contours for Full-Bore releases up to 6”*

*(*These results are limited to traditional DDT blast calculations)*

Table 4. Location Societal Risk

Building/Area	**Building/Area Societal Risk (fatalities/year)**				**% of Total**	
	Explosion	**Flash Fire**	**Jet Fire**	**Total**	**Building/Area**	**Cumulative**
Loading Station	**1.5E-4**	6.0E-8	2.8E-6	1.5E-4	36%	36%
Control Room	**1.3E-4**	9.2E-10		1.3E-4	31%	67%
Outdoor Area - Truck Loading		2.8E-5	**7.5E-5**	9.3E-5	22%	89%
Admin Building	**4.2E-5**	4.1E-10		4.2E-5	10%	98%
Outdoor Area - 1		**3.3E-6**	1.4E-6	4.6E-6	1%	99%
Outdoor Area - 2		**1.8E-6**	3.2E-7	2.1E-6	0.5%	100%
Totals	**3.2E-4**	**3.3E-5**	**7.9E-5**	**4.3E-4**		
	74%	**8%**	**18%**			

Table 5. Source Societal Risk

Source	**Source Societal Risk (fatalities/year)**				**% of Total**	
	Explosion	**Flash Fire**	**Jet Fire**	**Total**	**Source**	**Cumulative**
H2Unit-18-Loading	**1.6E-4**	3.2E-5	7.7E-5	2.5E-4	60%	60%
H2Unit-03-H2Separator	**9.7E-5**	3.3E-10	7.6E-9	9.7E-5	23%	82%
H2Unit-04-H2Separator	**6.8E-5**	1.9E-10	4.6E-9	6.8E-5	16%	98%
Remaining Sources	**4.6E-6**	9.1E-7	2.1E-6	7.4E-6	2%	100%
Totals	**3.2E-4**	**3.3E-5**	**7.9E-5**	**4.3E-4**		
	74%	**8%**	**18%**			

Table 6. Worker Individual Risk

Work Group	**Worker Individual Risk (APoD)**			
	Explosion	**Flash Fire**	**Jet Fire**	**Total**
Truck Driver	**1.4E-5**	2.7E-6	7.5E-6	2.3E-5
Operators	**1.4E-5**	5.7E-7	2.0E-7	1.5E-5
Lead Operator	**1.2E-5**	9.8E-11		1.2E-5
Admin	**8.8E-6**	8.7E-11		8.8E-6
Engineer	**8.8E-6**	8.7E-11		8.8E-6

In this case study, the Loading Station (36%) and Control Room (31%) incur the greatest risk onsite primarily from explosion hazards (Table 4). Neither building was designed with significant blast resistance in this model. While the loading station has lower occupancy than the Control Room, it incurs greater societal risk due to its closer proximity to the facility and loading area and the high probability of ignition sources that are present nearby.

This case study also indicated that three sources contribute 98% of onsite risk with hydrogen loading operations contributing 60% of that onsite risk (Table 5). Loading/unloading activities can pose a high likelihood of release due to the manual operations and number of connections occurring per year. Finally, the case study shows that truck drivers, operators, and the lead operator incur the highest individual risk being onsite and the other two work groups (Admin and Engineer) incur individual risk less than 1E-5.

Risk mitigation, if necessary, should focus on locations incurring the greatest risk and sources contributing the greatest risk[12]. If possible, personnel should be relocated further from the process consistent with safe and effective operations consistent with guiding principles of API RP 752 and RP 753. For buildings required to be located in close proximity to the process or loading such as the Loading Station, designing or upgrading the building's resistance to explosion hazards is another effective mitigation strategy. Source risk mitigation at hydrogen loading should focus on release prevention, detection, and isolation. Both building explosion mitigation to the Loading Station and Control Room as well as source risk mitigation at hydrogen loading could help reduce the risk incurred by truck drivers and operators.

Mitigation strategies are typically more costly to implement after the construction of a facility. Therefore, while mitigation strategies can and are identified and implemented during both the design and operation of facilities, utilizing the results of your FSS and QRA during the design process is preferred to identify and implement practical mitigation strategies.

Closing Statement:

Hydrogen production is expected to ramp up in the near future as an important chemical feedstock and fuel. Understanding the possible consequences and risks incurred to personnel at the facility and nearby area is vital to promote and ensure a smooth transition into the hydrogen economy. FSSs and QRAs are valuable tools to assess the consequences and risks to people and to prioritize optimal and cost-effective mitigation options.

In many applications, hydrogen is handled at either high pressure or cryogenic conditions, which may present additional safety risk. Therefore, the next paper in this series will specifically discuss hazards associated with high pressure hydrogen.

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