A Risk Informed Assessment of Hydrogen Dispensing in Warehouses

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Abstract: Hydrogen dispensing units are installed increasingly in warehouses to refuel fuel cell powered fork lift trucks. A risk informed assessment was undertaken to evaluate the adequacy of safety systems with a focus on property damage from explosions resulting from accidental hydrogen releases. A few scenarios covering the potential range of releases were evaluated. The explosion-related consequences in terms of overpressures and associated damages were taken from another modeling study. Based on failure rate data for generic and hydrogen systems, order of magnitude likelihoods were assessed for the release and explosion scenarios. The estimated property damage risk was evaluated against tolerable risk established using three independent criteria based on severity of consequences, a SIL (Safety Integrity Level) matrix, and loss experience in warehouses. Risk reduction opportunities were identified in terms of the integrity of the safety functions performed by the instrumentation.

Keywords: hydrogen dispensing, explosion hazard, warehouses, risk informed assessment

1. INTRODUCTION

As part of "green" solutions, hydrogen is becoming popular as a fuel in fuel cell driven systems. Fuel cell powered forklift trucks are increasingly used in warehouses. Loss experience with these systems thus far has been favorable. However, the practice of indoor dispensing of hydrogen introduces new fire and explosion hazards to the typical warehouse occupancy. Therefore, it is critical to understand and manage the associated property risks.

A detailed literature survey indicated that none of the codes and standards or published studies dealt specifically with the property damage and the associated risk from the hydrogen release and the consequent explosion in large enclosed spaces such as warehouses. In this connection, a study was undertaken to evaluate the hazard from hydrogen dispensing operation in large warehouses and the associated risk from property damage considerations, and to identify the risk reduction opportunities.

2. DISPENSING SYSTEMS

There is a variety of process design options for dispensing gaseous hydrogen. The fueling installations that we reviewed typically include a bulk liquid hydrogen storage, compressors and tanks for gaseous hydrogen, all of which are located outside the building. Gaseous hydrogen is hard-piped into the building where dispensers are generally located along the interior perimeter wall. Self-service hydrogen fuel-dispensing systems include key, code and card lock systems, which allow filling of permanently mounted fuel containers on hydrogen-powered vehicles.

3. SCOPE OF THE ANALYSIS

Standards such as NFPA 2 (2011) [1] and NFPA 55 (2013) [2] provide guidance on process and engineering safety requirements, and safety functions that need to be addressed in the design and operation of a hydrogen dispensing system. The main safety functions are related to prevention of dispensing in case of an abnormal condition, and shutdown and isolation of the dispenser in case of a hazardous condition. In addition to the sensors that monitor system variables such as pressures,

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temperatures, and flow rates, gas and fire detectors are provided to shut down and isolate the system in case of a hazardous situation.

The process design and safety instrumentation change with the process. Accordingly, process specific hazard analyses are needed to ensure that the process and safety instrumentation are adequate to address the needed safety functions. The analysis presented in this paper considers that the process design (including process and safety instrumentation) and operating procedures commensurate with good engineering practices and applicable codes and standards, and are subjected to appropriate hazard analysis. The focus is on identification of the integrity requirements of the needed safety functions based on the likelihood and severity of the consequences from hydrogen related explosions and fires. Identification and evaluation of engineering safety requirements and safety functions are not delved into in this paper.

4. SCENARIOS OF CONCERN

By considering that the available instrumented and safety systems will be adequate to address the needed safety functions, the initiating events of concern are releases of hydrogen from mechanical integrity failures of components of the dispensing system. No operator errors (such as opening of valves by mistake) that alone can lead to unmitigated releases are envisaged in the dispensing process, which is controlled by automated PLC-based instrumentation.

As long as the instrumented systems function per the design intent, hydrogen releases are either prevented or minimized, and no credible loss is expected. The mitigated scenarios are not of serious concern from a property loss exposure perspective. When instrumented systems fail to isolate the hydrogen supply in case of a hazardous condition, hydrogen continues to release until an action is taken or the system is emptied out. The focus of the analysis is on such scenarios where uncontrolled hydrogen releases are ignited leading to explosions and fires that can result in significant damage.

4.1 Mechanical Integrity Failures

A schematic of the type of hydrogen dispensing unit considered in this study is shown in Figure 1. The main header into the building connects to the individual sections of piping that supply hydrogen to the two dispensers operating at different pressures, viz., 25MPa and 35 MPa. In order to limit the maximum flow in case of an accidental release, restricted orifices (ROs) are provided on hydrogen piping: one on the main piping header outside the warehouse (RO1), and one on each supply header inside the warehouse to the dispensers (RO2 and RO3).

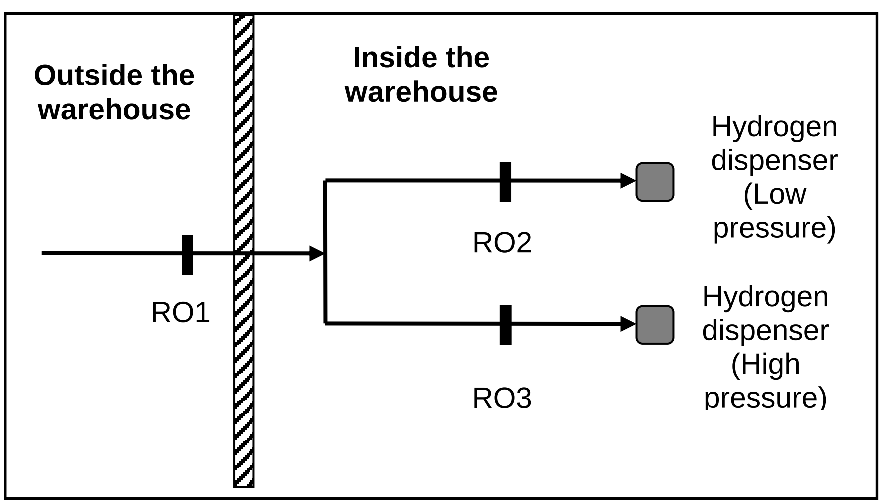

Figure 1: A Schematic of Hydrogen Supply to Hydrogen Dispensers

The dispensing system inside the building is comprised of a few meters of 1/2 - 3/8 inch diameter piping, appurtenances (such as valves and instrumentation), and hoses. The dispenser nozzle is a mechanical double-block-bleed valve that is independent of the electrical controls. In case of a pullout of the hose, the valves at the inlet of the hose (break-away valves) close automatically.

It should be noted that, based on the piping diameters (1/2 to 3/8 inch) and the pressures under consideration, in case of a "guillotine" type break of piping inside the warehouse, the flow rates could be up 20 to 30 kg/min, even though the rate can decrease over time considering the nature of the system and the inventory under consideration. However with ROs in place, such flow rates are reduced considerably, at the same time meeting the functional requirements of the dispenser. Based on the ROs considered in these evaluations, in general any break in piping downstream of the ROs on individual supply headers will release a maximum flow of 2 kg/min. While the ROs in the headers to the dispenser are expected to limit the flow, the exact flow would be dependent on the site specific design, and the size of the breach.

4.2 Releases

Assessment of consequences needs evaluation of a variety of releases, and consequent scenarios. The likelihoods of release, release rate, and duration of the release change with the scenario. Five constant release rates, viz., 0.25, 0.5, 1, 2, and 4[1] kg/min were examined to cover the range of scenarios of concern and interest.

The release duration considered in this study is 3 minutes - a moderate value. The warehouses of interest are attended 24 hours per day and 365 days per year. The remote and manual system shutdown switches recommended by codes and good engineering practices are expected to be readily accessible to personnel nearby. Sometimes, a timer facility is provided in the dispenser. Based on the available designs of the fuel cells, a 3-minute duration is considered adequate for dispensing the required quantity of hydrogen. Considering the nature of the warehouses and the dispersion of vapor cloud, an ignition is expected by 3 minutes after the release starts. In case of an ignition, further accumulation of hydrogen is not considered credible.

4.3 Ventilation

Typically, the amount of ventilation during a given release time is fairly small. Thus normal building ventilation would have little mitigating effect on dispersion and amount of flammable material available in the vapor cloud and in turn on the severity of explosion in general. However, the ventilation could effectively provide a degree of explosion venting since pressure buildups are slow during deflagrations in such large warehouses with relatively slow flames. Detonations, however, cannot be vented since the pressure increases so rapidly that the vent opening has no impact on the maximum pressure. Two cases were considered to evaluate the effect of ventilation for various release scenarios.

Case 1- Minimal/No Ventilation: Some warehouses may not have any designated mechanical ventilation.

Case 2 - Three air changes/hour: Ventilation rates change based on the climate and demands. Based on the observed ventilation rates at various warehouses, a ventilation rate of 3 air changes/hr was chosen in our evaluation as the second case.

5. EXPLOSION ANALYSIS

In order to generate the needed understanding of the consequences of potential explosions from uncontrolled releases of hydrogen, realistic modeling is needed for dispersion and explosion in large enclosed places. The results of a CFD modeling study undertaken by Bauwens (2013) [3] to evaluate

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[1] Even though the release rate of 4 kg/min was evaluated, based on the ROs considered in the design, it is not a possible release scenario.

hydrogen explosions in large warehouses were used in this analysis. The details of the basis of the modeling and the generated results used in the current study are described below briefly.

5.1 Basis of Modeling

A warehouse of size 62.4 m (W) x 62.4 m (L) x 8 m (H) was considered adequate to represent the warehouses of interest and to evaluate the physical effects of hydrogen release, dispersion and deflagration. The number and the height of racks considered were those of a typical warehouse.

The hydrogen dispenser was located along the wall of the warehouse a few meters from one of the corners. A corner provides the most conservative release location within the warehouse. If the release occurs away from the corner of the warehouse then the cloud expands in more directions and results in a thinner cloud with more mixing, and a lower mass above the LFL.

No obstructions were considered on the ceiling. Further, in order to create a conservative estimate of the amount of released hydrogen in the flammable mixture, it was assumed that the hydrogen released from the dispenser hits a solid surface, releases with low momentum and rises as a buoyant plume. The simulations were run for three-minute releases. The final mass of hydrogen above the LFL at the end of 3 minutes was used to estimate the maximum overpressure.

5.2 Results of Explosion Modeling

Overall, the consequences were observed to decrease with an increase in the size of the warehouse and the availability of ventilation.

5.2.1 Overpressures from Explosions

For all of the evaluated releases, the main source of damaging overpressure is the slow combustion of hydrogen, which without venting results in pressurization of the warehouse. In explosions, damage may also occur due to flame acceleration and the generation of a blast wave; however, for the releases evaluated in this study, the damage caused by the blast wave was estimated to be minor. The overpressure results were estimated for two cases: i) when only the mass of hydrogen above the LFL is consumed (P_{max} above LFL), and ii) when all of the hydrogen released is consumed (P_{max} Total). Table 1 summarizes the results of the dispersion simulations as well as the overpressure estimates generated for different release rates.

Table 1: Full Scale Unventilated Warehouse Simulation Results [3]

Release Rate (kg/min)	Total Mass Released (kg)	Total Mass Above LFL (kg)	Mass above LFL	P_{max} above LFL (bar/psi)	P_{max} Total (bar/psi)	Blast Wave Radius (m)
0.25	0.8	0.03	4.1%	-	0.01/0.145	-
0.5	1.5	0.34	22%	0.01/0.145	0.02/0.29	-
1	3.1	1.6	52%	0.02/0.29	0.04/0.58	5
2	6.1	4.1	67%	0.06/0.87	0.09/1.3	13
4	12.4	8.0	64%	0.12/1.74	0.18/2.6	23

The results presented in Table 1 are for the no ventilation case, i.e., the enclosure is well sealed without venting. In addition to the overpressure results, the table also includes estimates of the radius within which light damage may occur due to the generation of a blast wave. Blast wave estimations were done using an FM Global proprietary software package.

The effect of ventilation was examined by extrapolating peak overpressure results (considering only the mass above the LFL) with ventilation (three air changes per hour) and without ventilation, and also for variations in the warehouse size. Table 2 shows extrapolated peak overpressure results.

In addition to the pressure damage consequences of a hydrogen explosion, the possibility of unintended sprinkler activation due to the deflagration was also examined. Based on estimates, in some cases, it was found that all sprinkler heads located within the flammable cloud would likely activate following a hydrogen deflagration.

Table 2: Peak Overpressures Estimated for Additional Warehouse Geometries [3]

Height (m)	Area (m^2)	Volume (m^3)	1 kg/min		2 kg/min		4 kg/min	
			Closed (bar)	Ventilated (bar)	Closed (bar)	Ventilated (bar)	Closed (bar)	Ventilated (bar)
8	1950	15600	0.046	0.029	0.122	0.085	0.243	0.211
8	3900	31200	0.023	0.007	0.061	0.024	0.119	0.083
8	7800	62400	0.012	-	0.030	0.001	0.059	0.024
12.8	1950	24960	0.029	0.012	0.076	0.038	0.150	0.114
12.8	3900	49920	0.014	0.001	0.038	0.005	0.074	0.038
12.8	7800	99840	0.007	-	0.019	-	0.037	0.006

6. JET FIRE ANALYSIS

From a property loss exposure perspective, all hydrogen related fires (other than the fire following an explosion) are considered as ignition sources. SuperChems[2], a commercial software package was used to evaluate jet dispersions and jet fires.

The analysis also reviewed the potential overload on sprinkler systems from an ignition of combustibles initiated by jet fires. Based on the estimated size of the jet fires, they are not expected to result in large losses of concern on their own, provided adequate distances are maintained between the dispenser and the combustible storage.

7. LIKELIHOOD EVALUATION APPROACH

The likelihood of an explosion is a function of i) likelihood of accidental release of hydrogen; ii) failure of the available instrumented system to shut down and isolate the system to stop the release; and iii) failure of human intervention if the instrumented system fails. Since the perils of concern are fires and explosions, ignition likelihood and likelihood of a deflagration in case of an ignition are also important variables.

7.1 Release Likelihoods

After a detailed review of the compiled leak frequency data from literature, data from two studies by LaChance (2009) [4] and HSE (2012) [5] were mainly used in this study as they are relevant to the hydrogen dispensing systems under consideration.

LaChance (2009) [4] presents the results of a study performed to support the development of risk-informed[3] separation distances with focus on gaseous hydrogen storage facilities and the impact on the public at large. From the generic leakage frequency data compiled for various components, LaChance

[2] 'SuperChems™ Expert' is a commercial software package from ioMosaic Corporation.

[3] The risk under consideration in this study is related to personnel safety from jet fires.

(2009) [4] estimated hydrogen specific leakage frequencies using Bayesian analysis. Even though the focus was on personnel safety and outdoor facilities, the leakage frequency data developed by LaChance (2009) [4] was considered applicable for hydrogen dispensing units in enclosed spaces as well. LaChance (2009) [4] provides hydrogen release frequency data (median and 95% confidence values) for very small, minor, medium, major, and rupture leak sizes which correspond to leak areas of 0.01%, 0.1%, 1%, 10%, and 100% of total flow area respectively. Overall, the leak frequencies presented for hydrogen systems are one to two or even three orders of magnitude less than the compiled generic data. For larger leak sizes, hydrogen release estimates are much closer to general frequencies (by a factor of 2 to 4) as compared to smaller leak sizes. For hoses, there is a considerable difference between generic and hydrogen system leak frequencies.

In the dispensing system of our interest, even though piping and appurtenances are 1/2 to 3/8 inch size, maximum flows are restricted irrespective of the size of the breach in view of the presence of ROs in the piping. Any release from a rupture (100% leak area) to a medium leak (1% of flow area) in the piping or appurtenance is of concern since it can lead to an explosion and property damage. Thus the release likelihood values estimated are the sum of the frequencies of medium, major and rupture leakages. Minor and small leak frequencies are not included since minimal damage is expected from those scenarios.

Components of the dispensing unit being evaluated in this study are only those located in the building and include a few meters of piping, appurtenances, and hoses. The appurtenances considered include main isolation valve, control/shutoff valves on the main and supply headers, filters, restricted orifices, pressure control valve and relief valves on the low pressure header, and instrumentation connections. In order to be conservative, 95% confidence values were used for leak frequencies.

HSE (2012) [5] provides data on failure of hoses (leading to releases) with and without mitigation systems including break-away valves, reportedly collected from chlorine facilities. The H_2 incident database [6] reports around 19 incidents associated with hydrogen fueling stations. Even though the details are not available, three of them are associated with break-away connections. The break-away designs of a hydrogen hose are supposed to be more robust than that of a typical hose; however, based on the available data and our experience, high integrities couldn't be assigned to break-away valves. Using the data provided in HSE (2012) [5] and the loss experience, a range was considered for the failure likelihood of hoses and break-away valves.

Keeping in view the potential variations in the length of piping, and number of appurtenances and hoses from location to location, parametric estimations were performed and ranges of likelihoods were estimated.

7.2 Other Likelihoods

Hydrogen's flammability range (between 4% and 75% in air) is very wide compared to other fuels. Under optimal stoichiometric combustion condition, the energy required to initiate hydrogen combustion is much lower than that required for other common fuels. Tchouvelev (2008) [7] reported the ignition probabilities estimated for hydrogen by considering the available ignition probability data of other fuels, and their properties as compared to hydrogen. The ignition likelihood value provided by Tchouvelev (2008) [7] for enclosed areas was chosen considering that the warehouses are also enclosed spaces, and may not have any special ignition control systems.

Based on the observed trend in the industry, instrumented systems meant to address safety functions in dispensing systems are not considered as certified safety instrumented systems (SISs). Accordingly the instrumentation serving safety functions was not considered to provide even one order of magnitude (a factor of 10) risk reduction.

Considering the limitations in the available data due to the limited experience of the industry with hydrogen dispensing units, we recognize the uncertainty associated with various likelihood values chosen and estimated. Accordingly only order-of-magnitude likelihood values were used for our estimations.

8. ADEQUACY OF SAFETY ASSESSMENT

In order to assess the adequacy of safety systems, in addition to identification of safety functions, it is necessary to identify the needed and the available safety integrity of those safety functions. With the advent of PLC based controls, there is a need and opportunity to define the required integrity of the safety functions and also to evaluate the available integrity in the instrumentation serving the safety functions. SIL (Safety Integrity Level)[4] requirements for the safety functions depend on the process, instrumentation, operation, the material being handled and, importantly, the tolerable risk.

In view of the imprecise nature of the estimations, three independent approaches were used to establish tolerable risk and assess the adequacy of the available safety systems[5]. The first approach is based on the severity of consequences alone. The remaining two are risk informed approaches, where likelihoods are considered in addition to consequences. The second approach involved the use of a SIL (Safety Integrity Level) matrix. Based on the likelihood of the initiating event and the severity of the consequences of the scenario, SIL matrices are used to identify the needed safety integrity in terms of SILs for the safety functions to be performed by the instrumented systems. The third approach is based on the premise that loss experience can form the basis for the tolerable risk since such loss exposure has been tolerated by industry. An f-N curve generated from loss data provides the cumulative frequency of losses exceeding any specific loss $ value and thus the acceptable likelihood of a scenario or scenarios with greater than a specific property damage value.

In order to facilitate the implementation of the three above mentioned approaches, the needed data[6] were generated using the methodologies outlined in the previous section and FM Global's in-house data on warehouse related losses and property values. Warehouses were grouped into three size-based categories: small (<50,000 m^3), medium (50,000 to 100,000 m^3) and large (>100,000 m^3). The estimated overpressures as a function of the size of the warehouse were used to identify the extent of damages for the selected release scenarios for the three categories of warehouses. The effect of potential sprinkler system failure due to explosion was also included in property damage estimations. Typical property values per square footage and the associated business interruption values were used for these estimations.

8.1 Severity-based Approach

Table 3 provides a qualitative assignment of the severity of impact of over pressures as a function of the size of the warehouse, the presence of ventilation, and release rate of hydrogen. Table 4 presents the description of color coding that is used in Table 3.

8.2 SIL Matrix-based Approach

Figure 2 provides the SIL (Safety Integrity Level) matrix used in this study to identify the SIL rating of the safety function to be fulfilled by the safety instrumented systems (SISs). Tables 5 and 6 provide the descriptions of the probability and consequence categories used in Figure 2.

The SIL rating is based on the likelihood of an initiating event, the severity of the consequences, and the number of available non-SIS IPLs (Independent Protection Layers).

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[4] SIL (Safety Integrity Level) indicates the order of magnitude of risk reduction provided by the safety functions implemented in safety instrumented systems (SISs).

[5] Safety systems of interest in this study are the safeguards or mechanisms to prevent/minimize property damage and business interruption related losses.

[6] The in-house data and estimated numbers are not presented in this paper; however, the methodology and the conclusions drawn are presented for the benefit of the industry.

Table 3: Effect of the Size of the Warehouse on Extent of Damage

Release rate, kg/min	0.5	1	2	4	0.5	1	2	4
Continuous Ventilation	None	None	None	None	Present	Present	Present	Present
Warehouse size	Severity of overpressure							
Small warehouse	(yellow)	(orange)	(red)	(red)	(green)	(yellow)	(orange)	(red)
Medium	(green)	(yellow)	(orange)	(orange)	(green)	(green)	(green)	(orange)
Large	(green)	(white)	(white)	(white)	(green)	(green)	(white)	(white)

Table 4: Severity Rating for Consequences

Qualitative Severity rating	Color code used in Table 3
No concern	(white)
Negligible concern	(green)
Low impact	(yellow)
Medium impact	(orange)
Significant impact	(red)

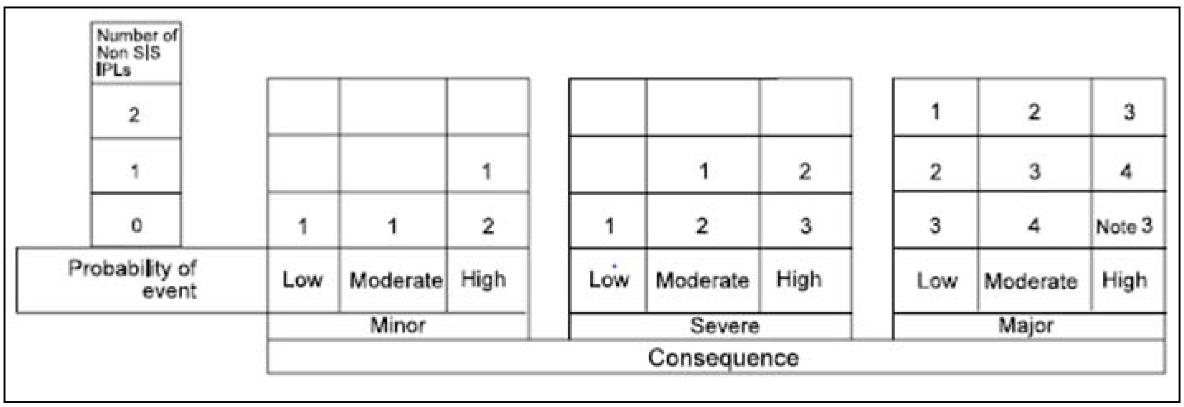

Figure 2: SIL Matrix [8]

Table 5: Consequence—Typical Categories [8]

Category	*Description*
Major	Substantial or total destruction beyond a local process area into the surrounding plant and shut down more than 3 months
Severe	Substantial damage mainly to a single process area and shutdown from 2 weeks to 3 months
Minor	Equipment damage and shutdown less than 2 weeks

8.3 Loss Experience-based Approach

An f-N curve such as shown in Figure 3, generated based on warehouse loss experience, was used to identify the exceedance frequencies for loss $ value of the property damage of interest.

Table 6: Probability of Process Upsets—Typical Categories [8]

Probability	*Type of Initiating Event*
High	Failure can be expected within the life of the plant. *Examples include process leaks, single instrument or valve failures, or human errors that result in releases of hazardous material*
Moderate	Failure or series of failures may occur with low probability within the life of the plant. *Examples include dual instrument or valve failures, a combination of instrument failure and human error or large releases in loading/unloading areas.*
Low*	Failure may occur with very low probability within the life of the plant. *Examples include combinations of multiple instrument failures and multiple human errors, or full-bore failures of small process lines or fittings.*

Note: * Multiple instrument or valve failure, multiple human errors, or spontaneous failures of vessels have lower likelihood but may also be considered in this group.

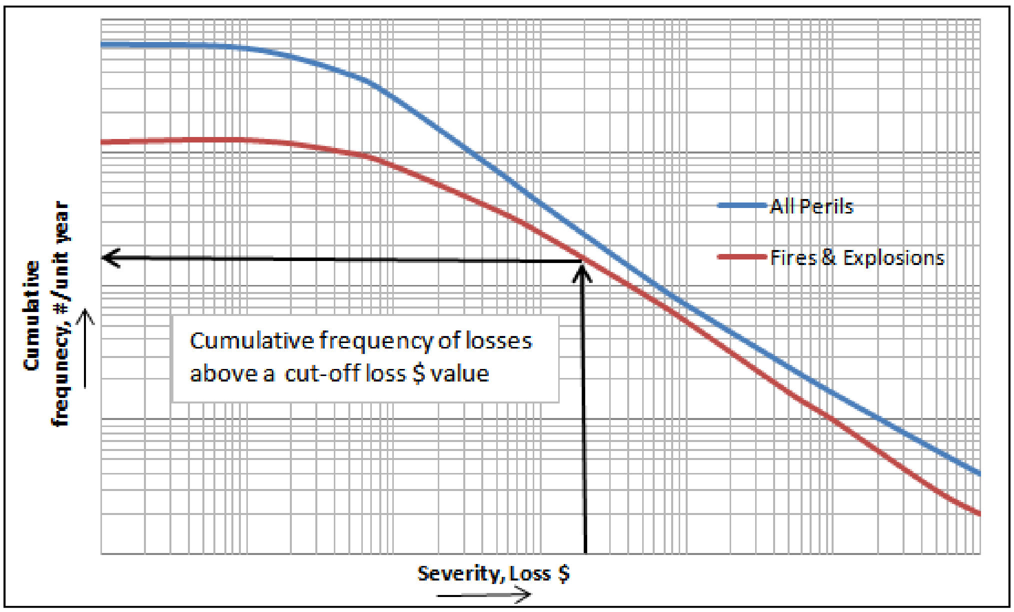

Figure 3: f-N Curve for all Perils and Fires & Explosions Losses

9. CONCLUSIONS

The conclusions drawn based on the estimated tolerable risk criteria, likelihoods and severities of explosions discussed in previous sections are provided in this section. Overall, hydrogen jet fires were not considered to affect the risk (property damage-based) at the estimated resolutions.

At this time, due to the limited operating experience on hydrogen dispensing systems, uncertainty is associated with the chosen likelihood values, and also the consequences considering the possible variations in release duration, nature of dispersion, and severity of the fire following explosion. However, the following risk reduction opportunities (RROs) are considered appropriate until significant experience is accumulated and data are collected.

9.1 Integrity of the Safety Functions

The risk reduction opportunities (RROs) related to the safety integrities of the instrumentation that serve safety functions are as follows. The following RROs assume that the instrumented safety functions provided in the design are adequate.

a. Based on the possible damage, for small (<50,000 m^3) warehouses without ventilation, it is necessary to have an assured SIL1[7] integrity for the safety functions performed by the instrumentation.

   In case of a hazardous condition, safety functions i) prevent the startup of the dispensing system and ii) shut down and isolate the dispensing system if in operation.
b. For medium (50,000 – 100,000 m^3) warehouses without ventilation and for small (<50,000 m^3) warehouses with ventilation, the damage potential is present, and thus it is desirable to have an assured SIL1 integrity for the safety functions performed by the instrumentation as mentioned above.
c. For the remaining warehouses, no certified safety instrumented systems are considered necessary to perform the safety functions.

If confirming the needed integrity in the PLC-based instrumentation is not feasible for any reason, dedicated hardwired Safety Instrumented System/s (SIS/s) may be considered to ensure the needed safety integrity. Even though gas detection and fire detection appear to be a separate layer of protection, generally they are connected to the same final control element (shutoff valve) to fulfill the safety function requirement; hence, they are not independent and cannot be given credit as IPLs.

9.2 Other Risk Reduction Opportunities (RROs)

9.2.1 Provision of Dedicated Ventilation System

Even at a release rate of 1 kg/min, the potential exists for damaging overpressures, and further means of mitigating the hazard such as explosion venting, or direct exhaust ventilation above the hydrogen dispenser could help. Considering the large size of the warehouses under consideration, we did not evaluate higher ventilation rates in the building as a potential solution. However, it may be worthwhile to evaluate spot/local ventilation directly above the hydrogen dispenser as an option to minimize the hazard associated with explosions. In such cases, the ventilation rate must be sufficient to keep the concentrations below the flammable concentration in the exhaust ductwork.

9.2.2 Maximum Flow Rates into the Building

If hydrogen dispensing systems have to be located indoors, the maximum hydrogen flows into the building should be controlled to the extent possible with the help of restricted orifices (ROs) inside and outside the building. If the allowed flow rates exceed the 2 kg/min value used in this study, additional evaluations and/or measures may be needed to address the risk.

9.2.3 Hydrogen Dispensing Loss/Failure Data

Gasoline and diesel dispensing has been in use for a long time, and this has resulted in codes and standards that have yielded an acceptable loss record. Even though hydrogen dispensing systems are more hazardous and the requirements may differ from indoor to outdoor dispensing systems, with adequate instrumentation, training, and administrative controls, hydrogen dispensing could also be implemented with an acceptable loss record. Accumulation of data is an important task in order to establish a quality basis for estimating hydrogen release frequencies and accordingly the needed layers of protection and their integrity.

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[7] SIL1 (Safety Integrity Level1) provides one order of magnitude of risk reduction.

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