RISK REDUCTION POTENTIAL OF ACCIDENT PREVENTION AND MITIGATION FEATURES

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ABSTRACT

Quantitative Risk Assessment (QRA) can help to establish a set of design and operational requirements in hydrogen codes and standards that will ensure safe operation of hydrogen facilities. By analyzing a complete set of possible accidents in a QRA, the risk drivers for these facilities can be identified. Accident prevention and mitigation features can then be analyzed to determine which are the most effective in addressing these risk drivers and thus reduce the risk from possible accidents. Accident prevention features/methods such as proper material selection and preventative maintenance are included in the design and operation of facilities. Accident mitigation features are included to reduce or terminate the potential consequences from unintended releases of hydrogen. Mitigation features can be either passive or active in nature. Passive features do not require any component to function in order to prevent or mitigate a hydrogen release. Examples of passive mitigation features include the use of separation distances, barriers, and flow limiting orifices. Active mitigation features initiate when specific conditions occur during an accident in order to terminate an accident or reduce its consequences. Examples of active mitigation features include detection and isolation systems, fire suppression systems, and purging systems. A concept being pursued by the National Fire Protection Association (NFPA) hydrogen standard development is to take credit for prevention and mitigation features as a means to reduce separation distances at hydrogen facilities. By utilizing other mitigation features, the risk from accidents can be decreased and risk-informed separation distances can be reduced. This paper presents some preliminary QRA results where the risk reduction potential for several active and passive mitigation features was evaluated. These measures include automatic leak detection and isolation systems, the use of flow limiting orifices, and the use of barriers. Reducing the number of risk-significant components in a system was also evaluated as an accident prevention method. In addition, the potential reduction in separation distances if such measures were incorporated at a facility was also determined.

1. INTRODUCTION

A concept being pursued in the National Fire Protection Association (NFPA) hydrogen standard development is to take credit for prevention and mitigation features as a means to reduce the separation distances. The reduction in the separation distance could be expressed as a reduction factor that represents the ratio of the separation distance without any mitigation feature to the separation distance with a mitigation feature credited. This paper presents some preliminary results of the quantitative risk assessment (QRA) for the following mitigation features taken individually (the risk reduction of combinations of these features has currently not been performed):

- Automatic leak detection and isolation
- Use of flow limiting orifices
- Use of barriers
- Reduction in the number of components

The risk reduction potential associated with these features was evaluated using the hydrogen system configurations and associated risk model used to establish the NFPA 2 separation distances [1]. Section 2 briefly describes the system configurations used in the analysis. The existing risk models for these configurations were modified to accommodate evaluation of each mitigation feature. The risk model is described in Section 3. The results of each evaluation are provided in Sections 4 through 7

2. FACILITY DESCRIPTIONS

Four hydrogen bulk gas storage systems were evaluated in the QRA used to determine the NFPA 2 separation distances. The four facilities were defined by industrial members of the NFPA 2 Task Group 6 (TG6) based on their knowledge of existing gas storage systems. As indicated in Fig. 1, two lower pressure systems consisted of three modules: a mobile tube trailer assumed to be at 20.7 MPa, a stanchion or product transfer module that connects the tube trailer to the facility, and a pressure control station for reducing (1.7MPa system only) or controlling the gas pressure. The storage facility ends at the source valve that separates the storage from the associated process equipment. The two higher pressure systems include additional modules: a compressor for raising the gas pressure from 20.7 MPa to the facility operating pressure and a high-pressure storage module.

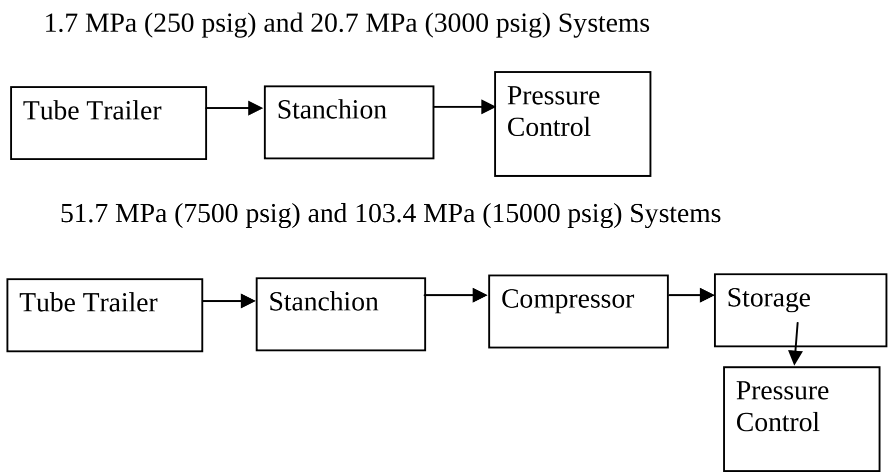

Figure 1. Simplified schematic of example gas storage modules.

3. RISK MODEL

The evaluation of risk for the example hydrogen bulk storage systems requires generation of models that delineate the potential accident sequences for hydrogen leakage events, the component leakage frequencies, additional data for phenomenological events such as hydrogen ignition, and an assessment of the consequences of the different accident sequences. The risk model is determined by the scope of the analysis. Only random component failures leading to hydrogen leakage were included in the current QRA scope. Leakages initiated by human errors, or natural events, or by other mechanisms such as automobile accidents were not included but are assumed included in the hydrogen leakage data. However, leakage contributions from valves, piping, gas cylinders, and connections were included in the analysis. Only accidents leading to exposure to ignited and un-ignited hydrogen jets were included. Overpressure events were excluded from the evaluation.

Figure 2 illustrates the accident event tree that was used for evaluating the hydrogen release scenarios from the example bulk storage systems. The accident sequence modeling is relatively simple and includes the frequency of a component leak, the probability of immediate ignition of the released hydrogen, the potential to detect and automatically isolate the leaks in certain portions of the facility, and delayed ignition of the hydrogen. The event tree illustrates the resulting consequences for each sequence which includes jet fires, flash fires following delayed ignition of hydrogen, and un-ignited gas releases.

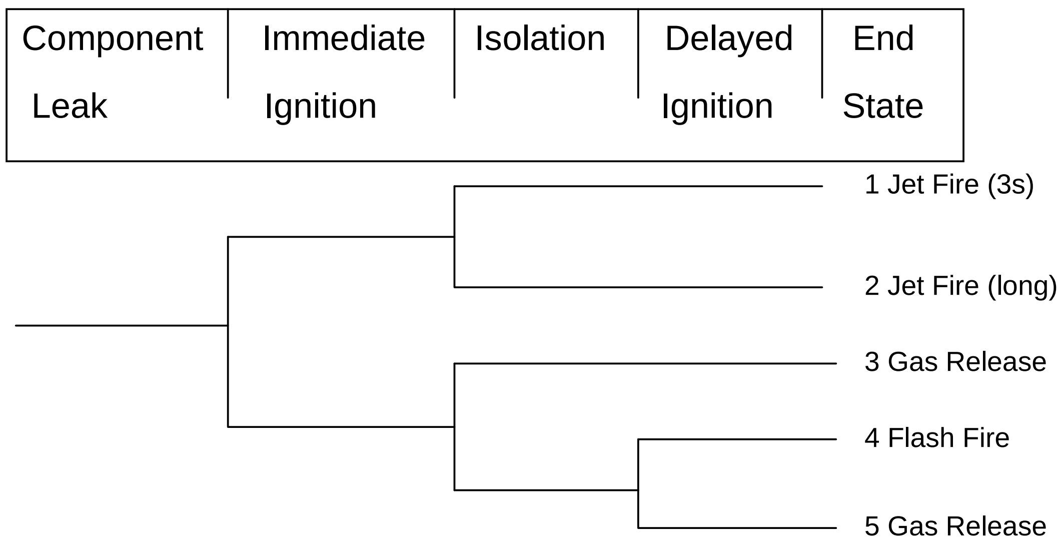

Figure 2. Hydrogen leakage event tree.

Immediate ignition of hydrogen following the occurrence of a leak results in a jet fire. If the leak is detected and isolation occurs, the duration of the jet was assumed to be 3 seconds (sequence 1 in Fig. 2). The consequences from short 3 second jet fires were assessed to be negligible based on an evaluation of thermal doses for this period. The thermal dose associated with a 25 kW/m^2 heat flux for 3 seconds is 220 $(kW/m^2)^{4/3}s$. Using both the Tsao and Perry [2] and Eisenberg [3] probit functions, the probability of fatality for this thermal dose is 3E-5 and 5E-8. When combined with the leakage frequency for each module, the probability of a fatality ranges from approximately 1E-11 to 1E-9.

If the leak is not detected or isolated, a continuous hydrogen jet fire occurs (sequence 2). The probability of detection and isolation failure was set to 0.1, independent of the means for detecting and isolating the system (see Section 4). Detection of leaks equal to or greater than 1% of the flow area associated with the largest pipe in each system downstream of the storage cylinders was assumed. A sensitivity study was also performed assuming that only detection of 10% or greater leaks in the largest pipe could occur.

If immediate ignition does not occur, the potential for delayed ignition was considered. If the leak is detected and isolated within 3 s, the potential for delayed ignition was assumed to be negligible resulting in a hydrogen gas release (sequence 3). If detection/isolation does not occur, a delayed ignition was considered possible. If delayed ignition occurs (sequence 4), a flash fire occurs and a person located in the 4% hydrogen envelope was assumed to be severely burned leading to a probability of fatality of 1.0. If delayed ignition does not occur, the sequence (5) results in a hydrogen gas release.

Supporting analyses and data are required to quantify the event tree shown in Fig. 2. Specifically, failure data is required to quantify the accident scenarios. The data required includes component leakage frequencies and hydrogen ignition probabilities. The hydrogen-specific component leakage data generated using Bayesian analysis and used in the NFPA analyses [1] was used to quantify the model. In addition to leakage data, phenomenological probabilities are also required. Specifically, the phenomenological event probabilities required for the risk assessment are the probability of hydrogen ignition and the probability a person would be exposed to a leak from a component. The ignition probabilities and personnel exposure probabilities from Ref. 1 were used in the study.

The QRA analysis also required the evaluation of the consequences for each hydrogen release scenario. As indicated previously, the consequences considered in the QRA were limited to exposure to radiant heat fluxes and flash fires. The Houf and Schefer model [4] was used to determine the resulting consequences for the hydrogen leakage events. The leak orientation was assumed to be directly at the target which results in the longest required separation distances.

4. DETECTION AND ISOLATION RISK REDUCTION POTENTIAL

Three different forms of detection and isolation are considered possible in a hydrogen bulk storage system:

- External flame and/or hydrogen detectors which can actuate one or more isolation valves
- Internal process measurement (e.g., high flow or low pressure) that actuate one or more isolation valves
- Excess flow valve that closes when flow exceeds a set amount

These three different forms of detection and isolation may not be viable in specific hydrogen system applications. Furthermore, the set point for detection may be variable for each method. Rather than evaluate each method specifically, a generic risk assessment was performed where it is assumed that each system would detect leaks equal to or greater than 1% of the flow area in the largest pipe connected to the bulk storage system and quickly isolate a portion of the bulk storage system. The probability of successful detection and isolation is assumed to be 0.9. Sensitivity calculations were performed for the case where the detection systems are only capable of measuring leaks equal to or greater than 10% of the flow area. Sensitivity calculation for the detection/system reliability was not performed as a 0.9 reliability appears to be sufficient to reduce the risk from hydrogen leaks.

The detection and isolation system evaluations were performed for the two system configurations shown in Fig. 1. The evaluation was performed for only one of the two pressures ranges applicable for each configuration. The results for the other two pressure ranges are expected to be very similar as the pressure/flow ratio between the systems is approximately the same.

4.1 20.7 MPa (3000 psig) Isolation Risk Results

Three isolation locations are considered for the 20.7 MPa system depicted in Fig. 1:

- At tube trailer manifold (inlet to stanchion)
- At the outlet of stanchion
- On the tube trailer cylinders

Isolation at the control module outlet (i.e., at the source valve) is represented by the base case (no isolation within the system).

Figure 3 compares the results when the isolation valve is located on the tube trailer manifold and leaks equal to or greater than 1% of the flow area are detectable to the results for the case where there is no detection and isolation capability in the system. Locating the isolation valve on the tube trailer manifold would not isolate leaks in the tube trailer. However, there is a significant reduction in risk from leaks downstream of the tube trailer. As indicated in Fig. 3, the isolation and detection system (with isolation at the tube trailer manifold) would reduce the separation distance from 14 m (the safety distance for a 4% H_2 envelope associated with a 3% flow area leak in a 18.97 mm diameter pipe) to

5 m if the same fatality risk level at the lot line of 2.2E-5/yr is maintained. The 5 m distance corresponds to a leak equal to 0.38% of the flow area of an 18.97 mm diameter pipe. The detection of 1% or greater leaks reduces the fatality risk by approximately 5E-6/yr for a person standing at 14 m.

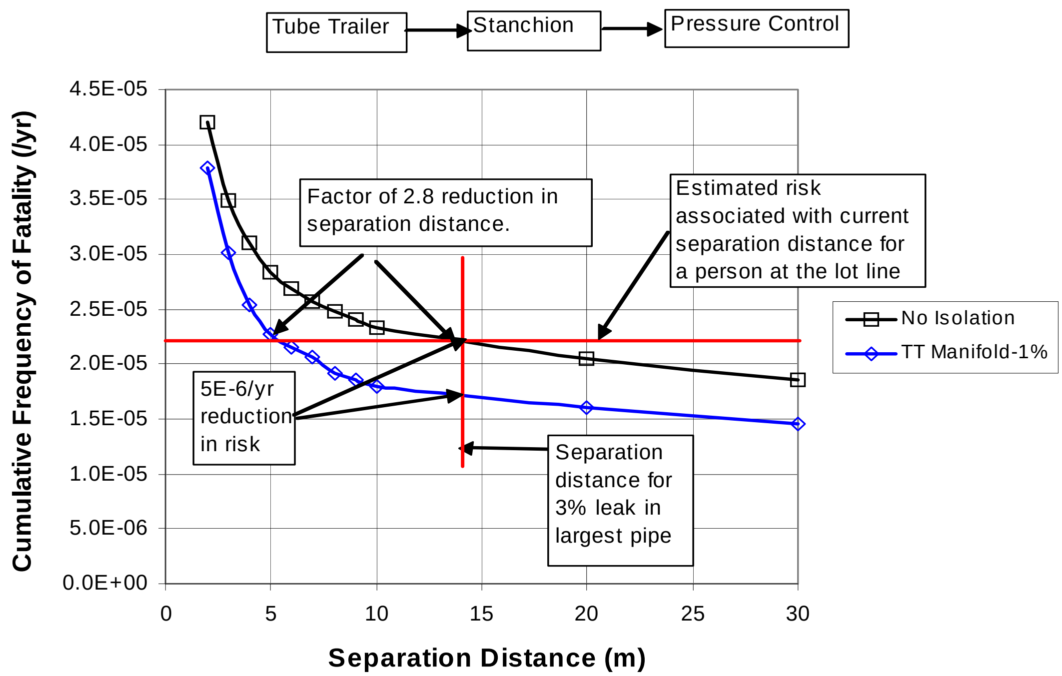

Figure 3. 20.7 MPa system risk, isolation at tube trailer manifold (leaks equal to or greater than 1% of the flow area detected).

Figure 4 shows the results for the 20.7 MPa system with isolation at the three different locations listed above. The reduction in separation distances range from a factor of 2 (7m, corresponds to 0.75% leak) for isolation at the stanchion outlet to 2.8 (5m, corresponds to 0.38% leak) for isolation at the tube trailer manifold, to 7 (2m, corresponds to 0.06% leak) if isolation is on the tube trailer cylinders. Note that a large risk reduction is possible if the isolation valve can be placed on each tube trailer cylinder since this location would mitigate almost all leaks in the system. Including isolation valves on each tube trailer cylinder is not highly feasible since it would require connecting the detection system to the valves and supplying power to the valves every time the tube trailer is exchanged. However, for fixed storage on the facility, this option is more feasible.

Figure 5 shows the results if detection is assumed to occur only for leaks equal to or greater than 10% of the maximum flow area in the system. The reduction in the separation distance decreases slightly for all 3 locations to 9 m when isolation is at the stanchion outlet, to 8 m when isolation is on the tube trailer manifold, and to 2.5 m if isolation is on the tube trailer cylinders. If the same separation distances are retained, the risk could be reduced by 5E-6/yr (isolation valve on the stanchion) to 1.7E-5/yr (isolation valves on the cylinders).

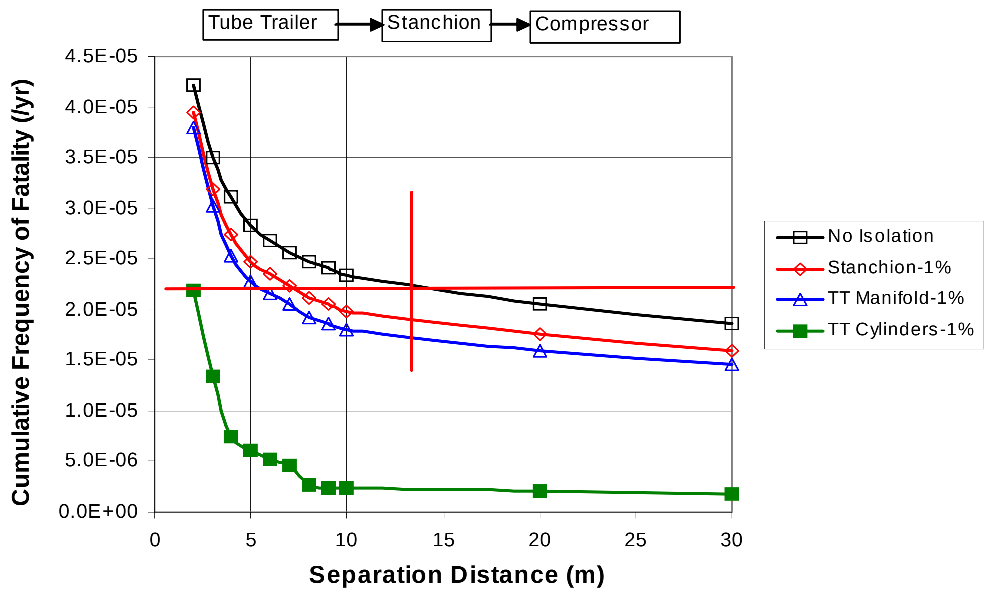

Figure 4. 20.7 MPa system risk results, isolation at different locations (leaks equal to or greater than 10% of the flow area detected).

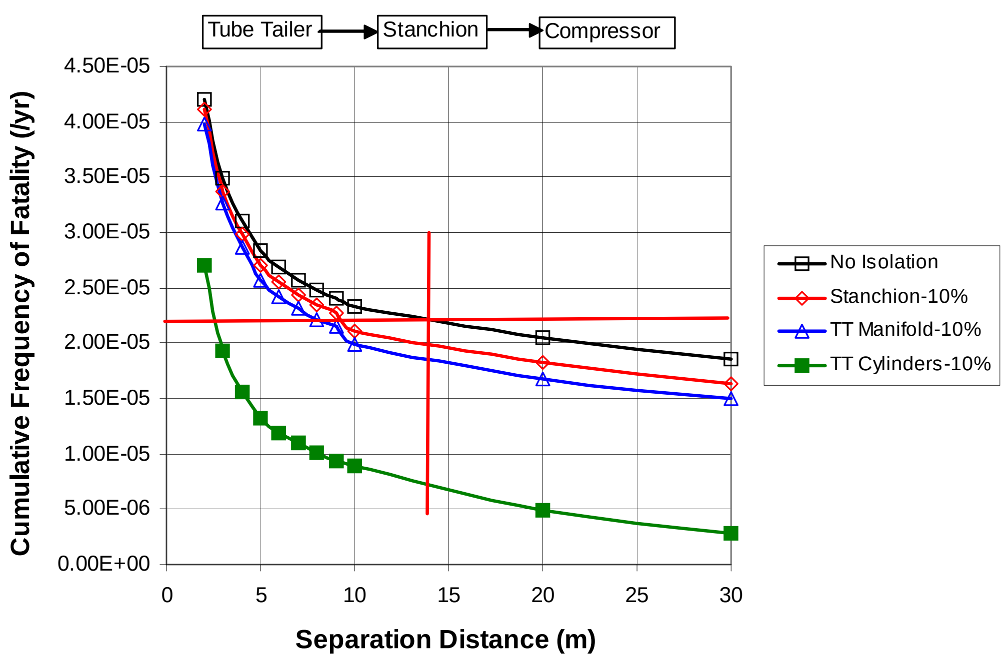

Figure 5. 20.7 MPa risk results for isolation of 10% or greater leaks.

4.2 103.4 MPa (15000 psig) Risk Results

Five isolation locations were considered for the 103.4 MPa system depicted in Fig. 1:

- At both the tube trailer and high pressure storage manifolds
- At the tube trailer manifold
- At the high pressure storage manifold
- At the outlet of stanchion
- At the tube trailer manifold and on high pressure storage cylinders

Isolation on both the tube trailer and high pressure storage cylinders is possible but has not currently been evaluated (expected to significantly reduce the risk from leaks and the required separation distances as was the case for the 20.7 MPa system). It is noted that isolation on the high pressure storage cylinders is more feasible than isolation on the tube trailer cylinders since the high pressure storage system is part of the fixed facility. For that reason, isolation valves on the high pressure storage cylinders in conjunction with an isolation valve on the tube trailer manifold was evaluated as a possible configuration. Isolation at only the compressor outlet would not isolate any leaks in the system and thus was not evaluated. Isolation at the control module outlet (i.e., at the source valve) is represented by the base case (no isolation within the system).

Figure 6 presents the results when isolation valves are located on both the tube trailer manifold and the high pressure storage manifold. Results are presented for detection of leaks equal to or greater than 1% and 10% of the flow area. Locating the isolation valve on the tube trailer manifold would not isolate leaks in the tube trailer. Similarly, an isolation valve on the high pressure manifold would not isolate leaks in the buffer storage cylinders. However, there is a significant reduction in risk from leaks downstream of both manifolds. As indicated in Fig. 6, the isolation and detection system (for detection of 1% leaks and with isolation at both manifolds) would reduce the separation distance from 10.4 m (the safety distance for a 4% H_2 envelope associated with a 3% flow area leak in a 7.16 mm diameter pipe) to 6.4 m if the same fatality risk level at the lot line of 3.4 E-5/yr is maintained. The 6.4 m distance corresponds to a leak equal to 1.14% of the flow area of a 7.16 mm diameter pipe. The detection of 1% or greater leaks reduces the fatality risk by approximately 5E-6/yr for a person standing at 10.4 m. If the leak detection capability is reduced to detecting leaks equal to or greater than 10% of the flow area the separation distance would reduce to 7.4m (corresponds to a 1.53% leak) if the same fatality risk level at the lot line is maintained. If the separation distance is maintained at 10.4 m, the detection and isolation system would reduce the risk to a person standing at the lot line by 4E-6/yr (detection of $\geq$10% leaks) or by 7E-6/yr (detection of $\geq$1% leaks).

Figure 7 provides the risk results for the other isolation locations in the 103.4 MPa system for the case where 1% or greater leaks can be detected. With isolation at the stanchion outlet, only leaks in the compressor can be isolated. As a result, the risk reduction potential is small and the resulting separation distance only decreases from 10.4 m (no isolation case) to 9 m which corresponds to a 2.25% leak size. With isolation on either the tube trailer or high pressure storage manifolds, the separation distance reduces to approximately 8 m (corresponds to a leak size of 1.8%). Isolation on the storage cylinders and the tube trailer manifold provides the biggest risk and separation distance reduction. The separation distance reduces to 4 m (corresponds to a leak of 0.44% of the flow area) and the risk would be reduced by 2.6E-5/yr if the current separation distance of 10.4 m was retained.

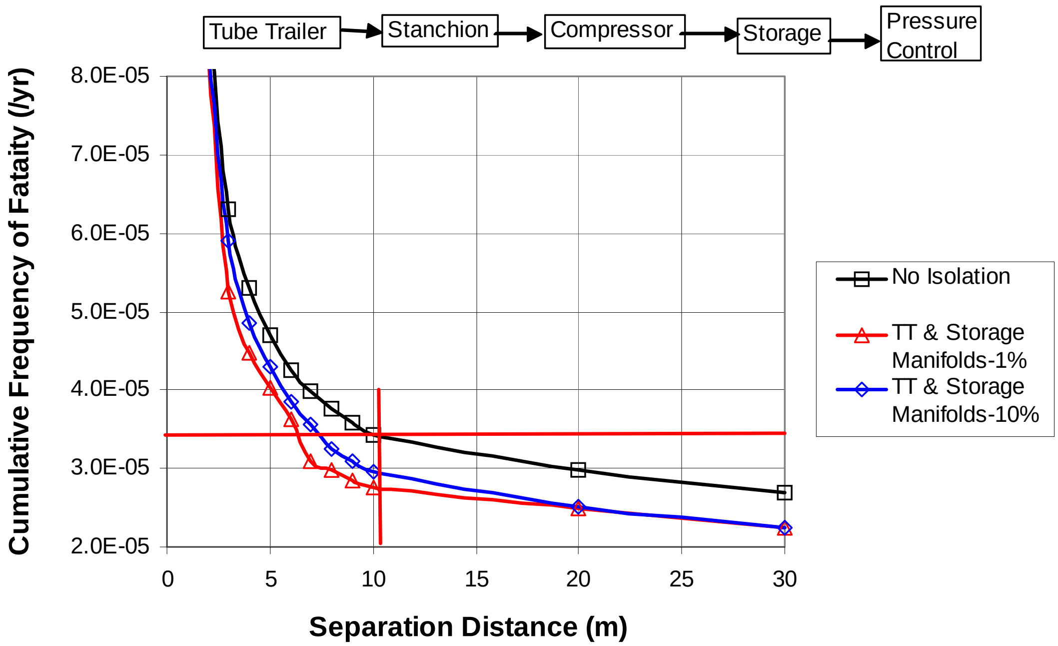

Figure 6. 103.4 MPa system risk, isolation at tube trailer and high pressure storage manifolds, detection sensitivity.

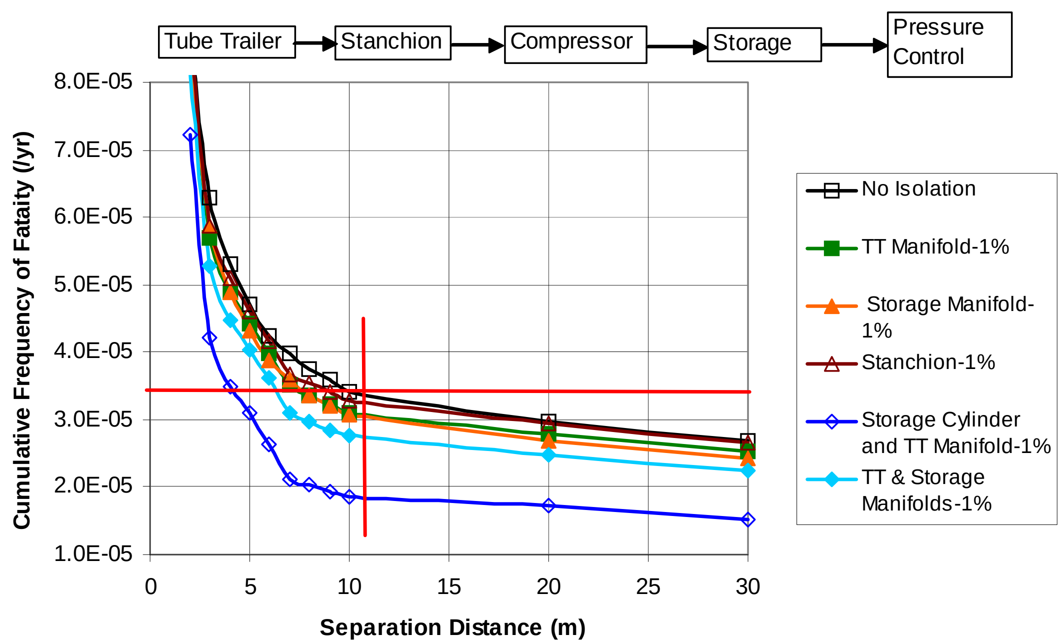

Figure 7. 103.4 MPa system risk results, isolation at different locations (leaks equal to or greater than 1% of the flow area detected).

5. FLOW ORIFICE RISK RESULTS

This section presents the results of the risk assessment when flow limiting orifices are used in a 20.7 MPa system. Figure 8 presents the results when a flow orifice is located in the tube trailer manifold. The location of the orifice at this location would limit the flow rate from leaks downstream. Two cases were evaluated: leaks limited to 1% and 10% of the largest pipe flow area in the system (18.97 mm in diameter). As indicated in Fig. 8, limiting flow to 1% of the flow area would reduce the separation distance from 14 m (no orifice, 3% leak) to 6 m (corresponds to a 0.55% leak) if the same fatality risk is maintained. If the flow restriction can only be limited to 10% of the flow area, the separation distance reduces to 9 m (corresponds to a 1.25% leak). As indicated in Fig. 9, locating a flow orifice on each tube trailer cylinder would result in a larger separation distance or risk reduction factors.

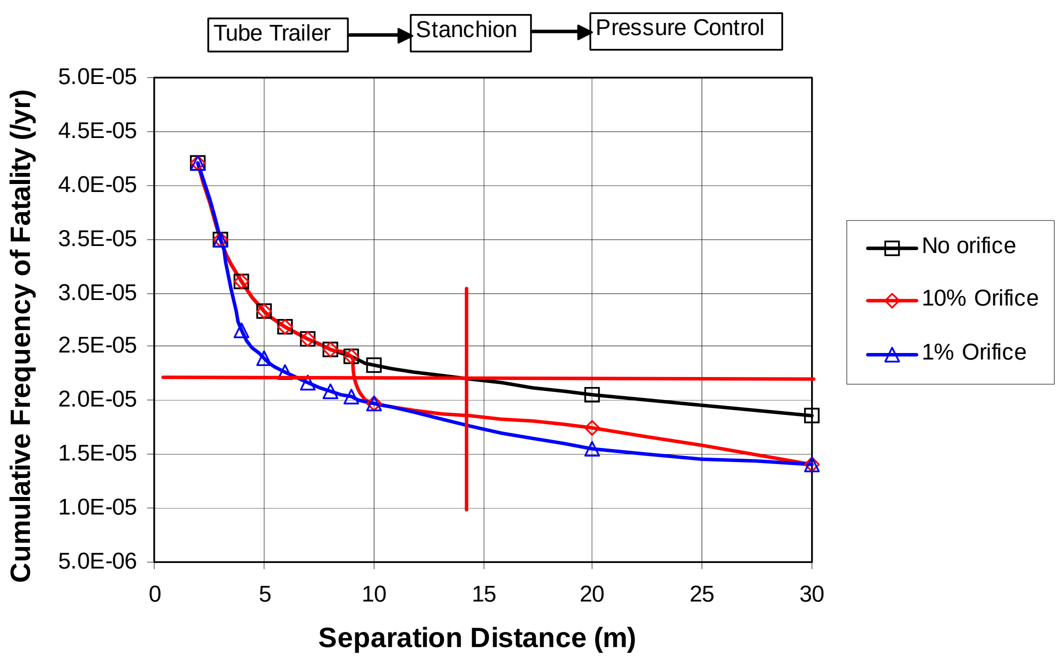

Figure 8. 20.7 MPa system risk results, flow limiting orifices at tube trailer manifold.

6.0 BARRIER RISK RESULTS

A previous assessment of the risk associated with barriers has been published [5]. The results of this analysis indicates that the use of properly designed barriers will remove the potential for direct contact with jet flames, reduce the distance of unignited jets, reduce the isosurfaces for various thermal radiation heat fluxes (see Fig. 10), and as indicated in Fig. 11, will not result in any substantial increase in pressure that would harm people or structures. Thus, barriers provide a means to reduce the risk to the public from unintended releases of hydrogen. This reduction in risk also allows for the opportunity to reduce the separation distances at a hydrogen facility. Estimates of the risk reduction potential were generated by using the risk model developed for evaluation of the separation distances selected for incorporation into the NFPA-2 and NFPA-55 hydrogen standards [1] and the consequence results reported in Houf et al., 2008 [6]. The system configurations and associated leakage frequencies utilized in Reference 1 and listed in Sections 2 and 3 were utilized in the barrier risk assessment, thus allowing for direct comparison of the risk with and without a barrier. The barrier wall was assumed to be 2.4 m high and separated from the hydrogen equipment by 1.22 m. Table 1 provides a comparison of the risk to an individual located at the facility lot line from a leak equivalent to a 3% of the maximum flow area in the hydrogen system.

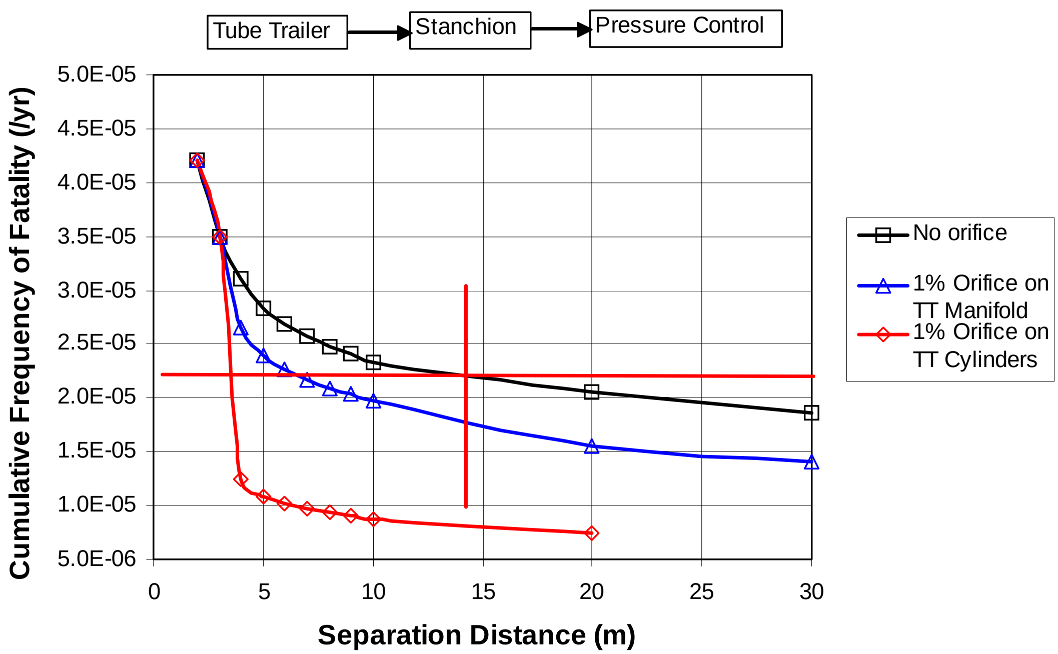

Figure 9. 20.7 MPa system risk results, 1% flow limiting orifice at different locations.

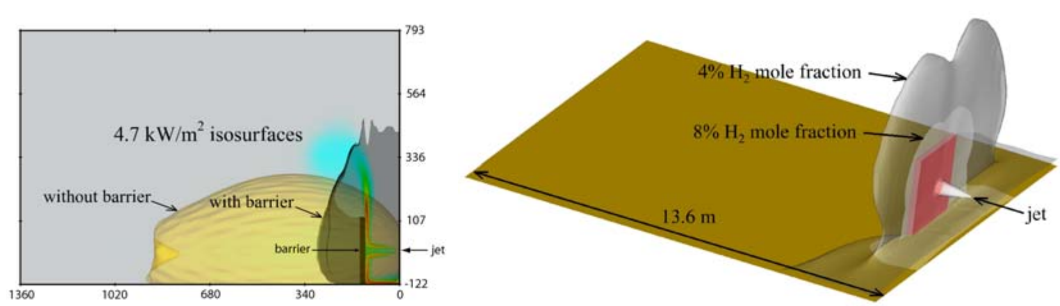

Figure 10. Barrier effects on radiation heat flux (left) and unignited hydrogen envelope (right).

As indicated in Table 1, the presence of a barrier can be used to reduce the risk to a person standing at the facility lot line. The use of a barrier can also be used to reduce the separation distances. For a risk level equivalent to the risk without a barrier, the separation distance to the facility lot line can be shortened to approximately 3.5 m (measured from edge of the facility and not the barrier) for the leak diameters shown in Table 1. This corresponds to reduction factors in the separation distance for the 20.7 MPA and 103.4 MPa of 4 and3, respectively. The 3.5 m separation distance corresponds to leak sizes of 0.19% and 0.34% for the 20.7 MPA and 103.4 MPa systems, respectively. The separation distance from the barrier would be approximately 2 m.

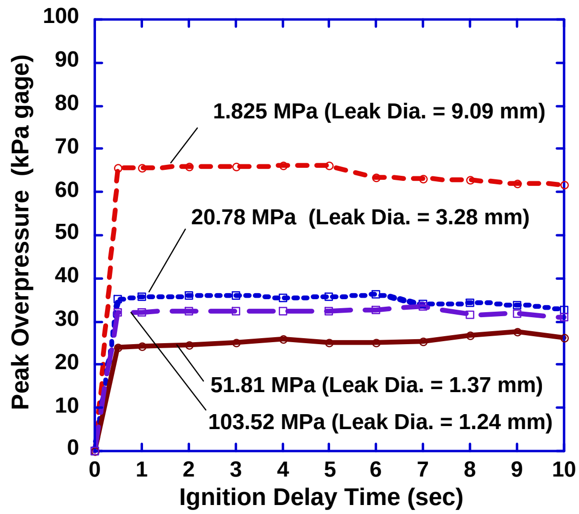

Figure 11. Peak overpressure behind barrier walls following hydrogen ignition for various pressure and leak diameters.

Table 1. Estimated risk reduction from the use of barriers.

System Pressure (MPa)	Leak Diameter[1] (mm)	Separation Distance to Facility Lot Line[2] w/o Barrier (m)	Individual Risk at Facility Lot Line (fatalities /yr)	
			No Barrier	Barrier
1.7	9.09	12.1	2.0E-5	5.4E-6
20.7	3.28	14.0	2.1E-5	5.5E-6
51.7	1.37	8.8	3.6E-5	1.1E-5
103.4	1.24	10.4	3.5E-5	1.0E-5

[1] Leak diameter corresponds to 3% of the largest flow area in the system
[2] Separation distance specified in NFPA-55, based on selected leak diameter.

7.0 REDUCTION IN THE NUMBER OF RISK-SIGNIFICANT COMPONENTS

The dominant risk contributors that were identified in the QRA documented in Ref. 1 include leakage from valves, joints, and compressors. Limiting the number of these components in a hydrogen system would reduce the potential for hydrogen leakage and thus reduce the associated risk. To illustrate how this might impact risk and separation distances, the risk for 110 MPa systems with different number of risk-significant components were evaluated. All the system components were assumed to be at the same pressure and have an internal diameter of 8 mm. The results are shown in Fig. 12 when a risk guideline of 2E-5/yr is used to select separation distances.

Figure 12 indicates that a system with a compressor (a component with a high leak frequency) will greatly increase the risk of a fatality and thus would require a relatively long separation distance. For this example, a similar system without a compressor would provide a lower risk to a person standing at

10 m or would require a shorter separation distance if the fatality risk level of 2E-5/yr was maintained (a reduction from 10 m to 4 m). A system with a reduced number of joints and valves in the system in addition to removal of the compressor would provide further reductions in risk or separation distances. These results indicate that separation distances in hydrogen codes and standards could be significantly reduced for very simple systems with a minimal of risk-significant components.

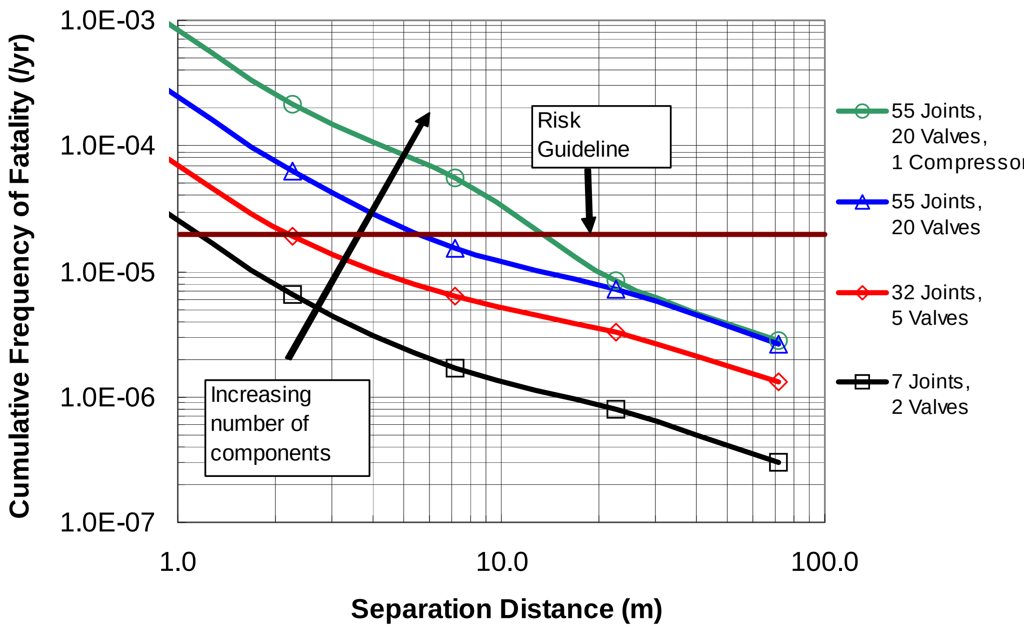

Figure 12. Risk reduction associated with reducing the number of high-risk components (110 MPa system with 8 mm inside diameter components)

SUMMARY

This paper presents some preliminary QRA results where the risk reduction potential for several active and passive prevention and mitigation features was evaluated. These measures include automatic leak detection and isolation systems, the use of flow limiting orifices, use of barriers, and limiting the number of risk-significant components. These features reduce the risk by either reducing the frequency of a hydrogen release or by reducing the resulting consequences. In addition, the potential reduction in separation distances if such measures were incorporated at a facility was also determined. Several observations are possible from the results:

The use of a detection and isolation system can significantly reduce the risk or separation distance at a facility by reducing the frequency of significant leaks. The effectiveness of the leak detection and isolation systems is dependent upon the detection capability and the location of the isolation valves. Locating the isolation valve as close to the source of hydrogen will provide the greatest risk reduction potential. In addition, the risk reduction potential increases if smaller size leaks (e.g., 1% of the system flow area) can be detected. A detection/isolation system reliability of 0.9 is sufficient to reduce risk.

Similarly, the use of flow limiting orifices, if the process allows, can also reduce the risk associated with a facility by reducing the maximum leak size that can occur downstream of the orifice location.

The orifices reduce risk by reducing the consequences of a leak in a system. Locating the orifices as close to the source of hydrogen will provide the greatest risk reduction potential.

Reducing the number of risk-significant components (e.g., joints, valves, and compressors) in a system will also reduce the risk by reducing the frequency of leakage events.

Barriers are effective in reducing the consequences associated with hydrogen releases. The use of properly designed barriers will remove the potential for direct contact with jet flames, reduce the distance of unignited jets, reduce the isosurfaces for various thermal radiation heat fluxes, and will not result in any substantial increase in pressure that would harm people or structures.

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