VIII.2 Risk-Informed Safety Requirements for H2 Codes and Standards Development

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Start Date: Fiscal Year (FY) 2002
End Date: Project continuation and direction determined annually by DOE

FY 2011 Objectives

(1) Scenario Analysis, Risk Assessments for Safety
   - Develop a scientific basis and the associated technical data for modifying or developing new codes and standards for the commercial use of hydrogen.
   - Develop benchmark experiments and a defensible analysis strategy for risk assessment of hydrogen systems.
   - Develop and apply risk-informed decision-making tools in the codes and standards development process.

(2) Hazards Mitigation Technologies for Hydrogen Applications
   - Determine the effectiveness of ventilation, active sensing, and similar engineered safety features.

(3) Codes and Standards Advocacy
   - Provide technical management and support for the Safety, Codes and Standards sub-program element.
   - Participate in the hydrogen codes and standards development/change process.

Technical Barriers

This project addresses technical barriers from the Codes and Standards section of the Fuel Cell Technologies 2007 Multi-Year Research Plan:

(F) Limited DOE Role in the Development of International Standards
(I) Conflicts Between Domestic and International Standards
(N) Insufficient Technical Data to Revise Standards
(P) Large Footprint Requirements for Hydrogen Fueling Stations
(Q) Parking and Other Access Restrictions

Contribution to Achievement of DOE Codes and Standards Milestones

This project will contribute to achievement of the following DOE milestones from the Codes and Standards section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

- **Milestone 21:** Completion of necessary codes and standards needed for the early commercialization and market entry of hydrogen energy technologies. (4Q, 2012)
- **Milestone 9:** Complete risk mitigation analysis for advanced transportation infrastructure systems. (1Q, 2015)

FY 2011 Accomplishments

- Expanded use and acceptance of quantitative risk assessment (QRA) to establish risk-informed codes and standards requirements.
- Harmonization of National Fire Protection Association (NFPA) and International Organization for Standardization (ISO) use of risk in establishing gaseous hydrogen facility separation distances.
- Evaluation of risk-reduction potential of accident mitigation features.

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Introduction

The purpose of this project is to enable risk-informed development of codes and standards for hydrogen fuel cell technology that is based on a traceable, scientific foundation. Our scenario analysis and risk assessment efforts focus on defining scenarios for the unintended release of hydrogen and quantifying the consequences through scientific experimentation and modeling. Quantitative risk assessment is used to identify risk drivers and risk mitigation strategies for the commercial use of hydrogen. We combine our validated models with QRA to support risk-informed decision-making in the code development process.

Approach

Risk-informed code development enables commercialization of and fuel cell and hydrogen technologies by identifying code requirements that will reduce the associated risk to socially acceptable levels. Our risk activities include QRAs of hydrogen facilities, development of risk management strategies, and global harmonization of performance-based standards. Efforts in FY 2011 have focused on (A) harmonization of the NFPA and ISO risk-informed approaches for establishing separation distances; and (B) risk prevention and mitigation feature analysis. The hazards involved with unintended releases of hydrogen may be mitigated through early detection technologies or suppressed through thermal management techniques and engineered responses. As a result of the analysis of accident prevention and mitigation features, we will be able to inform credit tables that will be assembled for separation distances and other requirements in hydrogen codes.

Results

Harmonization of NFPA and ISO Separation Distances

The development of a set of safety codes and standards for hydrogen facilities is necessary to ensure they are designed and operated safely. To help ensure that a hydrogen facility meets an acceptable level of risk, code and standard development organizations (SDOs) are utilizing risk-informed concepts in developing hydrogen codes and standards. Two SDOs, the NFPA and the ISO have been developing standards for gaseous hydrogen facilities that specify the facilities have certain safety features, use equipment made of material suitable for a hydrogen environment, and have specified separation distances. Under DOE funding, Sandia National Laboratories (SNL) has been supporting efforts by both of these SDOs to develop the separation distances included in their perspective standards. Important goals in these efforts are to use a defensible, science-based approach to establish these requirements and to the extent possible, harmonize the requirements. International harmonization of regulations, codes and standards is critical for enabling global market penetration of hydrogen and fuel cell technologies.

Efforts to harmonize the ISO and NFPA approaches for establishing separation distances have generally been successful as both used essentially the same risk approach for evaluating separation distances developed by SNL [1]. Similarly, the SNL consequence models and the hydrogen leak data generated by SNL [1] have also been generally adopted for use in the ISO separation distance evaluation. However, there are some important differences in the ISO and NFPA analyzes that make it difficult to compare the resulting separation distances. These differences include the scope of the application (i.e., bulk storage versus fueling station), the differences in the separation distance table format used in the specific standards (pressure ranges and exposures), the risk criteria used in the risk analysis, the utilization of component leak data in the risk assessment, and the importance placed on the risk results. Additional efforts occurred this year to understand the impact of differences in the data used in the two analyses and the effect on the resulting separation distances.

A major difference between the NFPA and ISO analyses was due to the component leak frequencies used in the analysis. The difference in the leak frequencies is related to the binning of the data used by SNL for generating hydrogen-specific leak frequency estimates using Bayesian analysis. A cursory analysis of the generic data by the ISO TC 197 [2] separation distance task leader was utilized in a non-rigorous statistical approach to generate the leak frequencies used in the ISO QRA. The ISO data analysis only utilized a subset of the available generic data, did not include any hydrogen-specific data, and did not evaluate the leak frequencies using a justifiable statistical approach. Instead, the limited review of the generic data was utilized to generate arbitrary, idealized linear (on a log–log plot) versions of leak frequency distributions generated by SNL. More importantly, the ISO leak frequencies were essentially shifted an order of magnitude based on the argument that some of the generic data was mis-binned and that a different binning scheme should be utilized.

In an effort to more rigorously evaluate the impact of the data binning performed by ISO and the resulting leak frequencies, SNL performed sensitivity studies in which both the generic and hydrogen specific data were rebinned, where appropriate, into the binning categories utilized in the ISO QRA. The rebinned data was then utilized in a Bayesian analysis to generate estimates of hydrogen component leak frequencies. The results for valves are highlighted in Figure 1.

A review of the generic leak frequencies for valves indicated that some of the data had been conservatively binned in the initial Bayesian analysis performed by SNL. The actual leak size represented in this data is uncertain. However, some of the data was rebinned into lower leak sizes, especially the data points identified by the ISO working group. In particular, many of the data points initially binned as ruptures (30% to 100% leaks) were rebinned into smaller leak categories. However, several data points remained as 100% leaks. A Bayesian analysis was performed using this revised data. As illustrated in Figure 1, the resulting hydrogen mean leak frequency curve has lower frequencies than those reported in Reference 1. However, the frequencies are not substantially less (less than a factor of 2 different) which does not justify, for example, using the 100% leak size frequency as representative of leaks in the 10% to 100% range (this is a non-conservative value for that range of leaks). In contrast, it would be conservative to utilize the leak frequency for 10% leaks to represent the leaks in that range. A more realistic result would occur if the original leak size bins from reference [1] were utilized

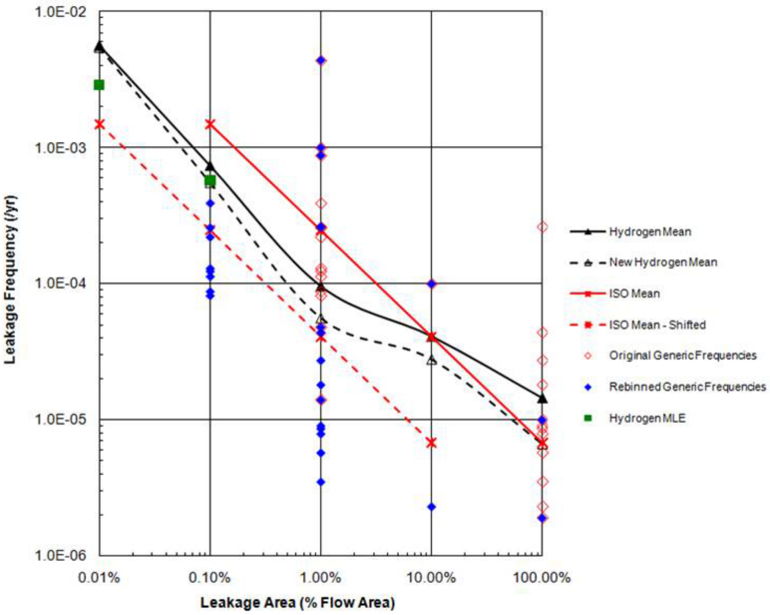

FIGURE 1. Results of Bayesian Analysis with Valve Data Rebinned

(i.e., leaks between 30% to 100% of the flow area are better represented by the leak frequency estimate for a 100% leak).

The results of the rebinning of data and Bayesian analysis for compressors resulted in similar results as for valves. The effect of the rebinning of the data for joints and hoses was negligible. Based on this more rigorous evaluation, the rebinning of selected generic data performed by the ISO working group does not provide an adequate basis for shifting the SNL-generated hydrogen leak frequencies reported in reference [1].

The ignition probabilities used in the QRA were also different in the NFPA and ISO QRAs. The NFPA QRA utilized ignition probabilities that changed with leak size and whether the ignition occurred immediately or was delayed. The NFPA ignition probabilities are provided in Table 1. The ISO risk model included a single ignition probability of 0.04 that was independent of leak size or ignition time. Although the selected ISO ignition probability was conservative over a range of leak sizes, as indicated below, its use skews the actual risk profile and the resulting selection of the separation distances.

TABLE 1. Hydrogen Ignition Probabilities used in NFPA QRA

Hydrogen Release Rate (kg/s)	Immediate Ignition Probability	Delayed Ignition Probability
<0.125	0.008	0.004
0.125–6.25	0.053	0.027
>6.25	0.23	0.12

To examine the significance of these differences in data, the impact of using the same component leak frequencies and hydrogen ignition probabilities used in the NFPA QRA on the ISO risk results and associated separation distances was evaluated. The results are shown in Figure 2 for four ISO-specified systems that have varying number of components most susceptible to developing leaks. As indicated in Figure 2, the resulting risk profiles are very different than from the ISO QRA and result in generally higher risk estimates for a person standing at a specified distance. Although the risk is higher for most of the systems/modules, the risk is acceptable over a range of separation distances. For example, the highest risk level is associated with the complex gas system (C). Using the ISO risk criteria of 1E-5/yr and 4E-6/yr, the associated separation distances are approximately 5 m and 9 m, respectively. The risk estimate for both of these distances using the NFPA data is 2E-5/yr. However, for the very simple gas system (VS), the ISO risk estimate is nearly identical to that predicted using the NFPA data.

Accident Prevention and Mitigation Feature Evaluation

A concept being pursued in the NFPA hydrogen standard development is to take credit for prevention and mitigation features as a means to reduce 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. QRA has been performed, using the hydrogen

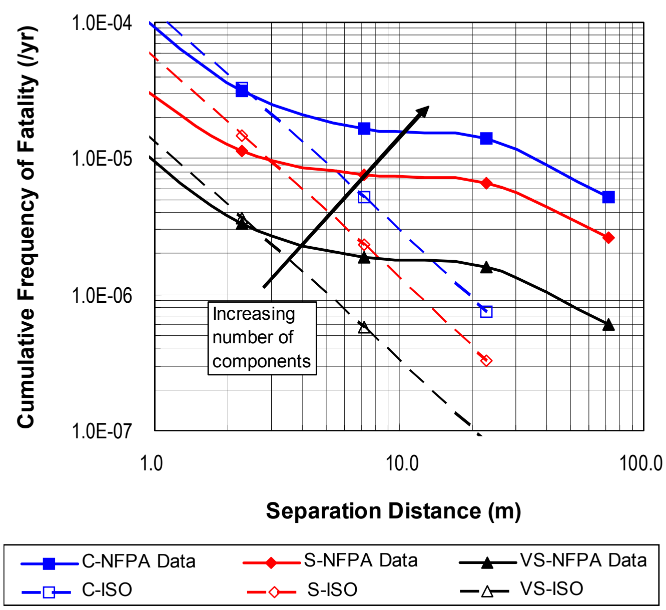

FIGURE 2. Results of Requantification of ISO QRA using NFPA Leak Frequency and Ignition Probabilities

system configurations and associated risk model used to establish the NFPA separation distances, 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 number of components

The risk reduction potential and impact on separation distances associated with barriers was reported in 2010. The risk reduction potential of the other features was evaluated using the hydrogen system configurations and associated risk model used to establish the NFPA separation distances [1]. Preliminary results are summarized in the following.

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 detection 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 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 risk reduction potential for a detection/isolation system is dependent upon the location of the isolation valve. The closer the isolation valve is to the bulk storage system the better is the risk reduction potential. Figure 3 shows the results with isolation at the three different locations in a bulk storage system operating at 20.7 MPa. The reduction in separation distances range from a factor of 2 (7 m, corresponds to 0.75% leak) for isolation at the stanchion outlet to 2.8 (5 m, corresponds to 0.38% leak) for isolation at the tube trailer manifold, to 7 (2 m, 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. Reducing the

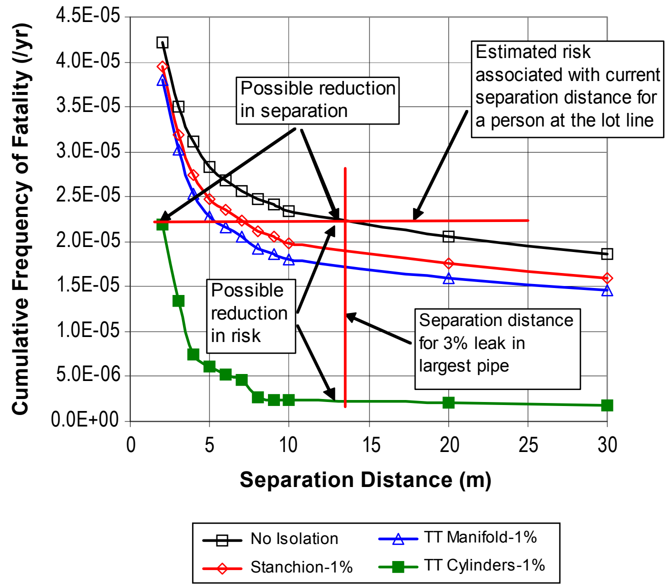

FIGURE 3. 20.7 MPa System Risk Results, Isolation at Different Locations (leaks equal to or greater than 1% of the flow area detected)

detection capability such that only leaks equal to or greater than 10% of the system flow area results in smaller risk and separation distance reductions.

Flow limiting orifices can also be used to limit the size of a leak and thus reduce the required separation distance. Similar to isolation systems, the location of the flow limiting orifice is important with regard to reducing risk and separation distances. For example, a flow orifice located in the tube trailer manifold in the 20.7 MPa bulk storage system modeled in the NFPA QRA would limit the flow rate from all leaks occurring downstream of the orifice. Using a flow orifice that is equivalent to 1% of the flow area would reduce the separation distance from 14 m (no orifice) to 6 m (a reduction factor of 2.33) 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 (a reduction factor of 1.56). Locating a flow orifice at locations downstream of the tube trailer manifold would result in lower separation distance reduction factors.

The dominant risk contributors that were identified in the NFPA QRA [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, 110 MPa systems with different number of risk-significant components was 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 Figure 4 when a risk guideline of 2E-5/yr is used to select separation distances.

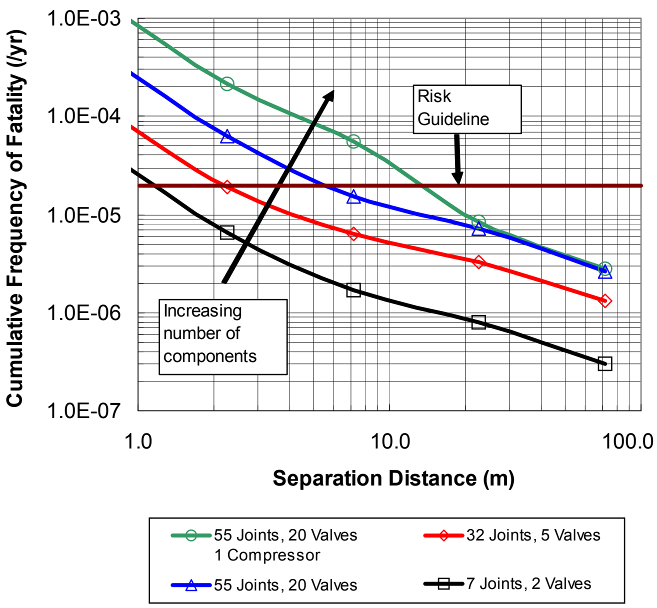

FIGURE 4. Risk Reduction Associated with Reducing the Number of High-Risk Components (110 MPa system with 8 mm inside diameter components)

References

1. LaChance, J., Houf, W., Middleton, B., Fluer, L., "Analysis to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards," Sandia Report SAND2009-0874, March 2009.

2. ISO/CD 20100, "Gaseous hydrogen – Fuelling stations," International Organization for Standardization, August 12, 2008.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.