IX.10 Risk-Informed Separation Distances for H_2 Facilities

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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 program management and support for the Safety, Codes and Standards 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 Refueling 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)

Accomplishments

Provided methods, data, and analytical support to International Organization for Standardization (ISO) technical committee (TC) 197 working group (WG) 11 Task Group 1 for the implementation of a risk-informed approach to determine separation distances for refueling facilities.

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Introduction

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 National Fire Protection Association (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, 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. The successful approach to risk-inform the separation distances in the NFPA standards [1] is a model for establishment of additional requirements by NFPA and other SDOs. In fact, ISO has generally adopted the SNL approach to determine the separation distances in ISO 20100, "Gaseous hydrogen – Fuelling stations" [2]. The efforts to support development of the ISO separation distances by providing methods, data, and analytical support to the ISO TC197 WG11 task group on separation distances are described subsequently. Differences between the approaches and data utilized in NFPA and ISO assessments are highlighted.

Approach

The approaches used in establishing the NFPA and ISO separation distances for gaseous hydrogen facilities are very similar but do have some important differences. Both use Quantitative Risk Assessment (QRA) techniques to evaluate the risk from unintended releases of hydrogen. The risk from the operation of a facility is the product of the frequency and consequences of all credible accidents and can be estimated using QRA. A QRA can be used to identify and quantify scenarios involving the unintended release of hydrogen, identify the significant risk contributors, and to identify potential accident prevention and mitigation strategies to reduce the risk to acceptable levels. A key mitigation feature is the use of separation distances. Under DOE sponsorship, SNL developed the data and methods that were used in quantifying both the frequency and consequence portions of the QRAs performed in both the NFPA and ISO analyses.

A significant difference between the NFPA and ISO approaches is that the NFPA approach is risk-informed while the ISO approach is more properly characterized as risk-based. A risk-informed process utilizes risk insights obtained from QRAs combined with other considerations to establish code requirements. Other considerations used in this risk-informed process include the results of deterministic analyses of selected accident scenarios, the frequency of leakage events at hydrogen facilities, and the use of safety margins to account for uncertainties in the data, methods, and scope of the risk evaluation. In contrast, a risk-based approach only utilizes risk to develop the requirements.

The separation distances in both the NFPA and ISO analysis are based on the selection of a hydrogen leak size that if ignited, would result in unacceptable risk to a person, structure, or equipment. It is generally accepted that separation distances should not be used to provide protection against rare events such as large, catastrophic ruptures. Separation distances should be selected to cover leakage events that may be expected to occur during the facility lifetime, especially small leaks that may occur frequently. It is also desirable to establish separation distances that are not too short and consequently result in unacceptable risk levels. In particular, the associated risk from leakage events that would result in consequences beyond the designated separation distances should be acceptable as determined by consensus. The risk-informed process used in the NFPA approach for selecting the separation distances explicitly included consideration of both the frequency of the selected leak size and the risk from larger leaks. In contrast, the ISO approach only included the evaluation of risk from leakage events (the frequency of expected leakage events was implicitly evaluated in the risk assessment but was not used in making any decisions). It is noted that in both analyses, some of the separation distances were not based on risk arguments. For example, in the ISO analysis the separation distances for large volume systems (i.e., >100 kg hydrogen) was based on the subjective argument that the distances should be greater than for the smaller systems.

The ISO risk-based approach utilizes the conceptual framework shown in Figure 1. In this approach, the cumulative risk from different leak diameters resulting in one or more specified consequence are evaluated against the separation distances required to protect people, equipment, or structures from a specified level of harm. The ISO analysis also included risk to structures and components with the potential for structural or component damage assumed to result in a fatality. The accidental releases of hydrogen were limited to leakage events from four types of components

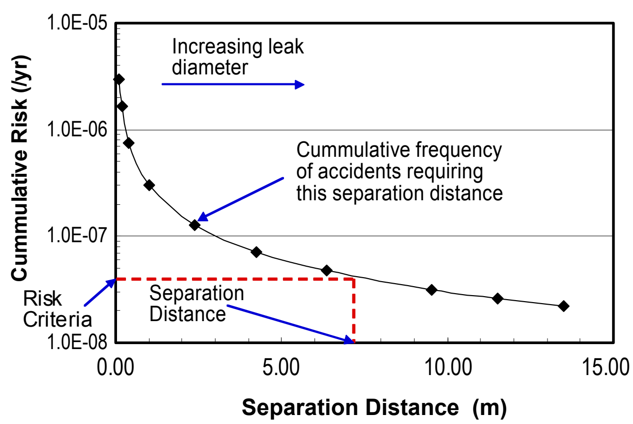

FIGURE 1. Risk-Based Approach for Establishing Safety Distances

(valves, compressors, hoses, and joints – pipes and tanks were excluded because they were not important risk contributors in the NFPA analysis). The consequences in both the ISO and NFPA analyses were limited to the effects of ignited hydrogen jets and exposure to an ignited hydrogen jet was assumed to result in harm to a target independent of the exposure period. In the ISO QRA, two selected risk acceptance criteria were used to establish the risk-based separation distances using the framework in Figure 1. The separation distances were generated for one of two selected consequence parameters that can result from a hydrogen jet: (1) the extent of the 4% hydrogen envelope or, (2) the exposure to an ignited hydrogen flame. Hydrogen leaks resulting in risk values equal to the risk criteria were used to select the separation distances for both consequence parameters.

In contrast, the leak diameter used as the basis for the separation distances in the NFPA approach was selected to encompass at least 95% of possible leakage events in typical hydrogen gas storage facilities. As a second criterion, the leak diameter was selected such that an event would not likely occur during the life time of the facility due to a low occurrence frequency (i.e., approximately 1E-2/yr). Although larger leaks would not be expected to occur, if they did, it would be desirable that the risk from these larger leaks to a member of the public standing at the selected separation distance be acceptable. Thus, the cumulative risk to the public from larger leaks was evaluated and compared to a single risk guideline, as opposed to the two risk criteria in the ISO approach, using the framework depicted in Figure 1. A risk guideline is essentially a soft risk criterion that allows consideration of uncertainty in the risk assessment when selecting the separation distances when using the framework in Figure 1. The NFPA risk evaluation included separate scenarios involving either early and late ignition of a hydrogen jet and added the risk to an individual from both scenarios to determine the separation distances (the ISO analysis only included one or the other scenario to evaluate the separation distances for each target but this was adequately compensated for by using a higher ignition probability that was equal to the average of the early and late ignition probabilities used in the NFPA analysis for a large release).

The risk measure evaluated in the NFPA QRA was the frequency of a fatality to a person assumed to be constantly present at the facility lot line from an ignited hydrogen jet. The fatality risk from all possible leaks in the modeled facility was evaluated and used to help select a single leak size (expressed as a percentage of the largest flow area in the system) that was used to determine the separation distance for all exposures included in the separation table. In contrast, the ISO analysis included the frequency of exposure of structures and equipments to hydrogen jets (to prevent escalation of a leakage event into a major incident; escalation was assumed to result in a human fatality) in addition to the potential for exposure of humans that would result in fatalities. Thus, different leak diameters were evaluated for different exposures and used to establish the resulting separation distances.

The performance of the QRAs in both assessments required selection of risk criteria/guidelines, establishment of needed data (component leakage frequencies and hydrogen ignition probabilities), and selection of a consequence model. Reference 1 provides a survey of fatality risk criteria that was used to select the risk guidelines utilized in the NFPA assessment. The selected fatality risk guideline of 2E-5/yr was based on three inputs: maintaining the risk at an equivalent level to gasoline stations, using a value that is consistent with countries that have established risk criteria, and limiting the risk from hydrogen releases to a fraction of the risk to an average person from accidental causes. The ISO analysis is using a slightly lower fatality risk criteria of 1E-5/yr for some exposures and a lower risk criteria of 4E-6/yr for selected "critical' exposures believed by some in ISO TC197 WG11 task group to require additional protection (e.g., large volumes of flammable liquids and air intakes in occupied buildings). There is no documented basis for the critical exposure criteria. It is also important to note that the ISO analysis used the two fatality risk criteria listed above for the criteria of exposure of equipment and structures to hydrogen jets based on the assumption that equipment damage would result in a fatality.

In both analyses, data and models generated by SNL were utilized. The hydrogen jet model developed by Houf and Schefer [3] was used in both the NFPA and ISO assessment to evaluate the harm distances associated with hydrogen jets. However, there are some differences in the two analysis in the data used in evaluating the frequency of ignited hydrogen jets. For example, different hydrogen ignition probabilities were used. The NFPA utilized ignition probabilities that changed with leak size and whether the ignition occurred immediately or was delayed. The ISO risk model included a single ignition model that was independent of leak size or ignition time. Although the selected ISO ignition probability was conservative, its use skews the actual risk profile and the resulting selection of the separation distances.

The component hydrogen leakage frequencies utilized in the NFPA were generated using a Bayesian statistical approach [4]. A Bayesian statistical method was selected for use in the data analysis for three reasons. First, this approach allows for the generation of leakage rates for different sizes of leaks which is a critical requirement for estimating the size of a leak to use as the basis for establishing separation distances. Second, it also generates uncertainty distributions for the leakage rates that can be propagated through the QRA models to establish the uncertainty in the risk results. Finally, it provides a means for incorporating limited hydrogen-specific leakage data with leakage frequencies from other sources (e.g., the nuclear and petroleum industries) to establish estimates for leakage rates for hydrogen components. An example of the generated hydrogen component leakage frequencies is provided in Figure 2. The component leakage distributions utilized in the ISO analysis are linear versions (on a log-log plot) of the values generated by SNL that as depicted in Figure 2 are conservative over the majority of the leak size range. The linearization of the SNL data distributions was performed to simplify the ISO analysis and allow for a method to generate alternate separation distances for facilities that are substantially different than the example facility used to establish the ISO separation distance table. However, the ISO linear leak frequency distributions actually used in the risk analysis were shifted an order of magnitude when used in the ISO risk analysis (illustrated in Figure 2). The shifting of the leak frequency distributions results in underestimating the risk associated with each leak size and under prediction of the resulting separation distances by a factor of 3 (e.g., it uses the risk for 100% leaks to generate the separation distance for 10% leaks).

Both the ISO and NFPA QRAs also require establishment of representative facilities for evaluating the frequencies of hydrogen leaks and the resulting risk. The NFPA analysis was focused on establishing separation distances for gaseous bulk hydrogen storage systems whereas the ISO analysis was for gaseous fuelling stations. A single facility description was used in the ISO evaluation while four configurations were used in the NFPA evaluation. Two operating pressures were evaluated with the ISO model while four pressures (one per model) were evaluated in the NFPA analysis. Thus, the representative facilities and pressures used in the analysis were substantially different. These differences also resulted in different separation distance table formats in the ISO and NFPA standards.

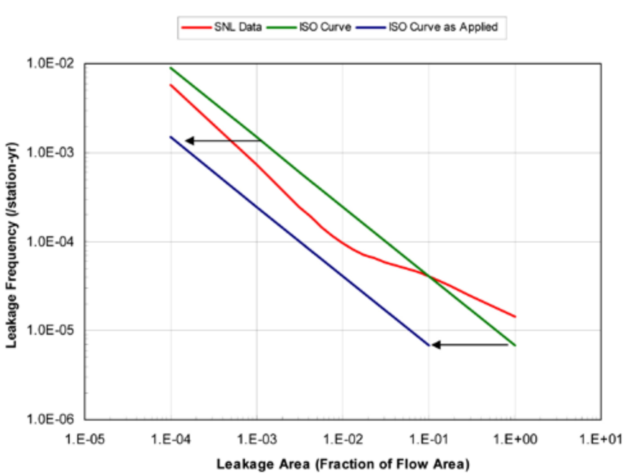

FIGURE 2. Comparison of Valve Leak Frequency Distribution used in NFPA and ISO Analyses

The NFPA example facilities had multiple components with diameters ranging from 7 mm to 52.5 mm. The ISO analysis used a single diameter for all components (8 mm) in the facility. In addition, the NFPA analysis assumed that the entire facility was collocated while the ISO analysis divided the facility into modules that were assumed to be adequately separated. The risk from leaks for each module was evaluated and compared with the risk criteria. By separating the gaseous fuelling station in this fashion, the risk to an individual can be underestimated for stations that are not separated. These differences in the assumed facility separation result in significant differences in the estimated leak frequencies and associated risk for the facilities. It also makes it difficult to compare the resulting separation distances.

Results

Comparison of the separation distances generated in the ISO and NFPA analysis is not possible due to the differences in the scope of the application (i.e., bulk storage versus fuelling station) and the differences in the separation distance table format used in the specific standards (pressure ranges and exposures). However, it is informative to compare the leak size, in terms of the percentage of the flow area, used to determine the separation distances. As indicated in Table 1, the fraction of the flow area used to determine the ISO separation distances for both the regular and critical exposures (i.e., based on a 1E-5/yr and 4E-6/yr risk criterion, respectively) are substantially less than the 3% of the flow area utilized by NFPA (calculated using a 2E-5/yr risk guideline). There are several contributors to the difference including different risk criteria, different facility configurations, separation of the gaseous fuelling station into separate modules, different ignition probabilities, and most importantly, the difference in the application of the hydrogen leak frequencies. Table 1 shows that the leak area would increase by an order of magnitude if the linear leak frequency distributions generated by ISO TC197 WG11 task group were not shifted in the ISO risk assessment. The resulting leak sizes for the ISO regular exposures are closer to the value selected for the NFPA standards.

Conclusions and Future Directions

As indicated above, the efforts to harmonize the ISO and NFPA approaches was generally successful as both used essentially the same risk approach for evaluating separation distances developed by SNL. Similarly, the SNL consequence models and the hydrogen leak

TABLE 1. Comparison of Leak Sizes used to Determine Separation Distances in ISO and NFPA Standards

System Type	Example Systems	Leak Size (% of Flow Area)			
		ISO Base Case		ISO Analysis with Correct Data	
		Regular Exposure	Critical Exposure	Regular Exposure	Critical Exposure
NFPA	System with a hydrogen tube trailer, pressure regulator module, compressor, and buffer storage area	Not Applicable (NA)	NA	3.00%	NA
ISO					
Complex Gas System	Cascaded buffer storage system	0.42%	1.30%	4.20%	13.05%
Simple Gas system	Cylinder pack	0.16%	0.48%	1.57%	4.84%
Very Simple Gas System	Pressure regulation module	0.03%	0.09%	0.28%	0.87%
Complex Large Storage system[1]	Hydrogen tube trailer	0.75%	3.00%	0.75%	3.00%
Simple Large Storage System[1]	Large hydrogen storage (e.g., 100 m^3)	0.38%	1.50%	0.38%	1.50%
Compressor System	Compressor plus connections	0.65%	1.81%	6.46%	18.11%

[1] The leak sizes for these systems were not evaluated using the ISO risk model. They were subjectively selected.

data generated by SNL were used in both evaluations, although generally conservative approximations of the leak frequencies were generated for the ISO analysis. However, the application of the ISO leak frequency distributions in the QRA underestimates the risk and associated separation distances. International harmonization of regulations, codes and standards enables global market penetration of hydrogen and fuel cell technologies. Toward this end, efforts will continue to evaluate the effect of other differences between the NFPA and ISO analyses in order to harmonize the methodologies and the resulting separation distances to the greatest extent possible.

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