# Hydrogen Quantitative Risk Assessment

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Project End Date: Project continuation and direction determined annually by DOE

## Overall Objectives

- Develop algorithms, models, and data to enable industry-led codes and standards revisions to be based on a strong, traceable science and engineering basis.
- Develop hydrogen-specific quantitative risk assessment (QRA) and consequence models and methods to support regulations, codes, and standards decisions and to enable alternate means of code compliance, such as performance-based design.
- Develop the Hydrogen Risk Assessment Model (HyRAM) toolkit to provide a rigorous, documented basis for analyzing hydrogen infrastructure safety with QRA and consequence modeling.

## Fiscal Year (FY) 2019 Objectives

- Develop and integrate quantitative risk assessment flexibility into HyRAM.
- Pursue open-source license for HyRAM 2.0.
- Develop liquid hydrogen leak frequencies.
- Draft white paper based on workshop discussions on hydrogen vehicles in tunnels.
- Host NFPA 2/55 bulk hydrogen storage task group.

## Technical Barriers

This project addresses the following technical barriers from the Hydrogen Safety, Codes and Standards section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan[1]:

- A. Safety Data and Information: Limited Access and Availability
- F. Enabling National and International Markets Requires Consistent Regulations, Codes, and Standards
- K. No Consistent Codification Plan and Process for Synchronization of R&D and Code Development
- L. Usage and Access Restrictions—Parking Structures, Tunnels and Other Usage Areas.

## Contribution to Achievement of DOE Milestones

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

- Milestone 2.4: Publish a methodology for estimating accident likelihood. (2Q, 2013)
- Milestone 2.8: Publish risk mitigation strategies. (2Q, 2014)
- Milestone 2.11: Publish a draft protocol for identifying potential failure modes and risk mitigation. (4Q, 2014)
- Milestone 2.13: Develop and validate simplified predictive engineering models of hydrogen dispersion and ignition. (4Q, 2015)
- Milestone 2.19: Validate inherently safe design for hydrogen fueling infrastructure. (4Q, 2019)
- Milestone 4.7: Complete risk mitigation analysis for advanced transportation infrastructure systems. (1Q, 2015)

[1] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

- Milestone 4.8: Revision of NFPA 2 to incorporate advanced fueling storage systems and specific requirements for infrastructure elements such as garages and vehicle maintenance facilities. (3Q, 2016)

## FY 2019 Accomplishments

- Integrated QRA flexibility into HyRAM by allowing direct input of external fault tree results in order to expand the usability of HyRAM by allowing the incorporation of better information and applications beyond refueling stations.
- Obtained an open-source license for HyRAM 2.0 and released installer and source code to the public so that users can obtain free software without a lengthy licensing process, users and researchers can view and verify the models used, and researchers can use and contribute improvements to code.
- Hosted the NFPA 2/55 bulk hydrogen storage task group and developed an improved leak frequency estimation method to incorporate hydrogen-specific data in the future so that risk assessments and code requirements for liquid hydrogen stations can be improved.
- Developed a white paper based on workshop discussions on hydrogen vehicles in tunnels; developed an expanded version of the white paper to include comparison to other alternative fuels.
- Incorporated uncertainty into tunnel risk assessment to better reflect unknown aspects of tunnel crash scenarios and better communicate how the risk assessment might change with improved information instead of changing point estimates.

## INTRODUCTION

DOE has identified consistent safety, codes, and standards as a critical need for the deployment of hydrogen technologies, with key barriers related to the availability and implementation of technical information in the development of regulations, codes, and standards. Advances in codes and standards have been enabled by risk-informed approaches to create and implement revisions to codes, such as National Fire Protection Association (NFPA) 2, NFPA 55, and International Organization for Standardization (ISO) Technical Specification (TS)-19880-1. This project provides the technical basis for these revisions, enabling the assessment of the safety of hydrogen fuel cell systems and infrastructure using QRA and physics-based models of hydrogen behavior. The risk and behavior tools that are developed in this project are motivated by, shared directly with, and used by the committees revising relevant codes and standards, thus forming the scientific basis to ensure that code requirements are consistent, logical, and defensible.

## APPROACH

This work leverages Sandia's unique experimental and modeling capabilities and combines these efforts with stakeholder engagement and international leadership. Sandia develops the algorithms and methods for performing QRA, including scenario development, likelihood and consequence analysis, and risk quantification. Sandia's Turbulent Combustion Laboratory develops and validates predictive engineering models for flame initiation, flame sustainment, radiative heat flux, and overpressures. The resulting QRA and hydrogen behavior models are integrated into the HyRAM toolkit to enable consistent, traceable, and rigorous risk and consequence assessment. The hydrogen behavior and QRA models in HyRAM are then applied to relevant technologies and systems to provide insight into the risk level and risk mitigation strategies with the aim of enabling the deployment of fuel cell technologies through revision of hydrogen safety, codes, and standards.

## RESULTS

### Additional Flexibility Added to QRA Calculations in HyRAM

The QRA calculations in the HyRAM software are based upon a set fault and event tree structure; while these were made to be as general as possible, they do not allow for a more complex estimation of leaks. This is because the software assumes that leaks can occur randomly from pieces of equipment, and a given leak frequency is estimated for each type of equipment and for each leak size. However, a more complex fault tree with better information might be available to a user. Previously, HyRAM was unable to accept this more complex leak frequency estimation; while it was theoretically possible a user could estimate the base leak frequency and input this into HyRAM, this would greatly complicate the calculation and introduce many opportunities for error.

Thus, the development team implemented a change in the software that would allow for a user to enter in the results of a sperate fault tree analysis into HyRAM directly by overriding the generic fault tree within HyRAM. Specifically, the user is now able to enter in an annual leak frequency for a given leak size directly. Thus, a user with a more complex leak frequency estimation can still take advantage of the consequence and risk calculation features of HyRAM while not being limited to a generic leak frequency estimation. Furthermore, a different leak frequency override could be entered for each leak size. This means that if a user has better information about a particular leak size, but no specific information about other leak sizes, they can still benefit from the generic defaults within HyRAM while also being able to take advantage of their updated information where appropriate.

There are many situations in which a user may have better information. If a separate fault tree analysis (using different software) was developed, the results from this analysis can be entered into HyRAM. The default fault trees within HyRAM can assume random leaks from certain pieces of equipment and estimate full-bore releases from a vehicle dispenser. Different leak scenarios or diverse pieces of equipment may have more complicated leak fault trees; it may be useful to calculate different ways in which a leak could develop rather than assuming an overall average leak frequency for different scenarios. By allowing for this external analysis to be entered into HyRAM, this updated methodology enables users to alter the risk analysis for different applications.

### Released HyRAM 2.0 as Open Source

Sandia had multiple discussions with the DOE Fuel Cell Technologies Office on the long-term plan for HyRAM 2.0 and beyond. Several options were discussed, including eliciting industry for funding, giving the software to a university, or providing HyRAM in an open-source format. Informal discussions were had with some current HyRAM users as to how they use HyRAM and what they would be willing to pay for in the future. The outcome of these discussions is that the ability of HyRAM to be commercialized is dependent upon it being a requirement, such as for permitting, for example in NFPA 2 or another code or standard. Based on these discussions, it was decided that the HyRAM development team would pursue an open-source license for HyRAM 2.0 and beyond.

An open-source license and copyright for HyRAM were obtained in FY 2019. The HyRAM 2.0 software version was completed. This version was based on code that is hosted publicly as open source. This version of the software also contained the custom fault tree capabilities discussed above. A working version of the executable was built (for Windows) and the source code was cleaned up to support publishing externally. The HyRAM external website was edited to point to the correct points of contact and links to the installer and source code. An email was sent to all HyRAM users to announce this new release.

### Support for NFPA 55/2 Bulk Hydrogen Storage Task Group and Development of Liquid Hydrogen Leak Frequencies

Sandia hosted the NFPA 2 and 55 Bulk Hydrogen Storage Task Group meetings where the liquid hydrogen (LH2) separation distance progress was discussed, in addition to safety equivalencies and station deployments to date. As a result of those discussions, Sandia began to develop liquified natural gas (LNG) leak frequencies to begin the discussion on LH2 leak frequencies. The goal of this work is to develop LNG leak frequencies that gas suppliers can review in the hopes that they will provide hydrogen-specific data in the future. This required compiling failure rate information from multiple sources for liquid components. The leak failure data will be used to develop a quantitative risk analysis for a liquid hydrogen station. Sandia also started monthly meetings with industry members to obtain leak frequencies. As part of this, a template was developed to begin discussions on leak frequencies. The template identified components, leak sizes, number of leaks, and number of operating years or demands.

Lacking industry data, Sandia began to test the methodology using LNG and other data. Sandia used this generic data to illustrate the process, demonstrating how generic and LH2-specific information could be combined using a Bayesian process. Having the methodology coded and demonstrated will allow for a quick analysis of the industry data once it is provided. The leak failure data will be used to develop a quantitative risk analysis for a liquid hydrogen station and support the Bulk Hydrogen Storage Task Group under NFPA 2.

### Workshop and White Paper Draft on Hydrogen and Other Alternate Fuel Vehicles in Tunnels

Chris LaFleur attended a meeting December 19, 2018, in Boston with the Secretary of the Massachusetts Department of Transportation to discuss the Sandia tunnel analysis report and answer any questions. Executives from major automakers and gas suppliers attended and spoke about their commitment to clean energy and Massachusetts. The Secretary highlighted her commitment to moving toward cleaner fuels as well. Chris LaFleur presented the results of the report and answered the Secretary's and her staff's questions about the analysis performed.

Sandia and Fuel Cell Technologies Office staff met with Federal Highway Administration representatives to kick off a joint effort around alternate fueled vehicles in tunnels in the United States. A path forward is to create a comprehensive alternative fuel vehicle tunnel safety roadmap that will collect and address all stakeholder concerns. This roadmap will include light-, medium-, and heavy-duty vehicles powered by hydrogen fuel cells, compressed natural gas, propane, and advanced chemistry batteries. The outline for this document was drafted and reviewed by the steering committee. The draft of this literature search document was sent to the steering committee for review. This combined federal effort will allow forward progress with public safety as a priority.

### Incorporated Uncertainty into Hydrogen Vehicle Crash Tunnel Risk Assessment

As part of the effort on assessing the risk of hydrogen vehicles in tunnels, a previous analysis using an event tree framework was updated. This analysis looked at what could potentially happen if a fuel cell vehicle was involved in a vehicle crash in a tunnel. Based on what could potentially happen, probabilities and likelihoods can be quantitatively estimated for different potential consequences of a crash. These consequences are then categorized by if the hydrogen does not add any hazard (as in, it either is not released or does not ignite), if it adds hazard to the crash scenario (as in, it immediately ignites to form some kind of jet fire), or if it adds a potentially catastrophic hazard (as in, it does not immediately ignite and could accumulate first). The event tree used in this analysis is shown in Figure 1.

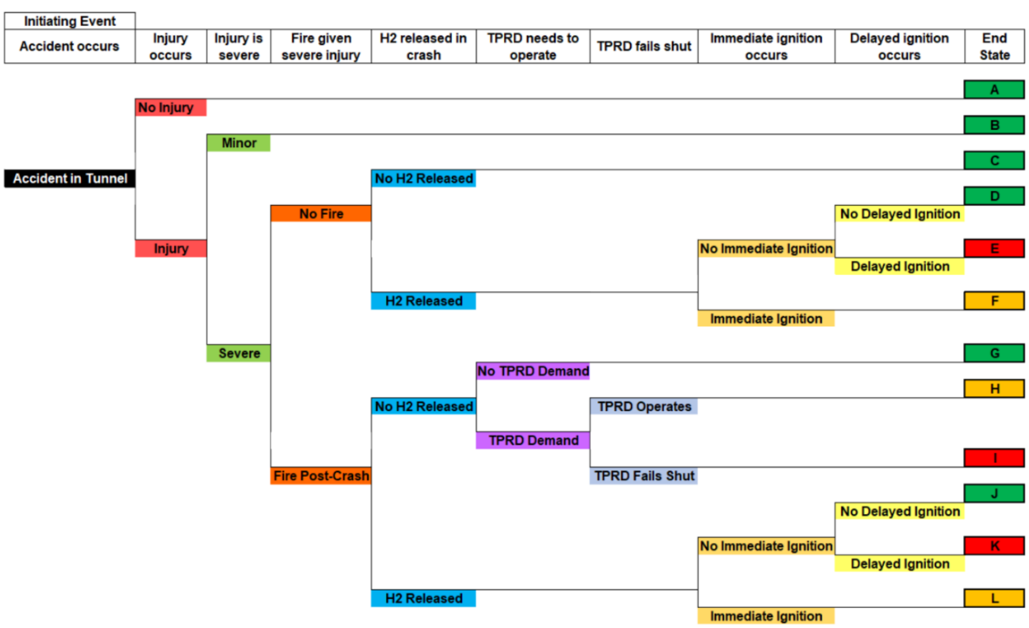


Figure 1. Event sequence diagram for a crash in a tunnel that involves a hydrogen fuel cell vehicle

One issue with this type of analysis is that, by necessity, it uses data (probability and frequency values) from many disparate sources. Additionally, estimates on certain probabilities may be based on a relatively large amount of data (and should therefore be relatively certain) whereas some probability estimates are almost completely unknown. If both probability estimates are used as single values, this varying amount of uncertainty between the two is completely lost; a single uncertain parameter could end up driving the results and conclusions.

To address this issue, each branch point on the event tree was assigned a probability distribution. That is, instead of having a single value for the probability of one branch vs. the other, there is instead a range of possible values that the probability could be, with a different likelihood for different values of the probability. Then a random sample of each probability distribution was taken to estimate the probability value at each branch point for a single "trial" of the event tree. This sampling was repeated thousands of times to assess the distribution of likelihood values for how probable each final end state is. This results in complementary cumulative distribution functions or exceedance probability curves for each end state scenario. These curves are shown in Figure 2.

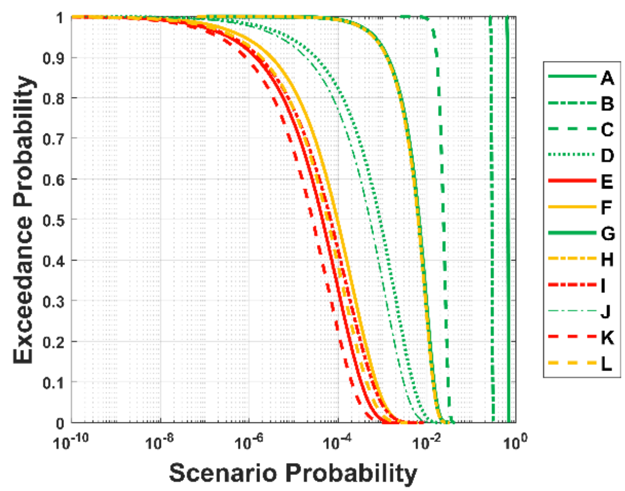


Figure 2. Characterization of uncertainty around the event tree scenario probabilities using exceedance probability curves

These results indicate that the catastrophic (red) scenarios are orders of magnitude less likely than other scenarios. These results also indicate that Scenario H (a jet fire) is the most likely scenario that results in additional hazard due to hydrogen. This indicates that a jet fire due to a vehicle crash should be analyzed further to better understand the risk of this particular hazard. This risk assessment of hydrogen fuel cell vehicles in tunnels has been accepted for publication in the journal *Fire Technology*.

## CONCLUSIONS AND UPCOMING ACTIVITIES

The HyRAM software has been released publicly and with more flexible leak frequency estimation options. The current reduced-order hydrogen release behavior model in the HyRAM toolkit relies on an equation of state that is only valid down to a temperature of 150 K. The use of reduced-order models for cryogenic hydrogen releases will allow for liquid (or near-liquid) hydrogen releases to be modeled directly, enabling physical and risk-assessment models to consider liquid systems in a QRA or risk-informed assessment. Recent efforts have led to improvements in the COLDPLUME model and more thorough validation with experimental data. This model needs to be implemented into the HyRAM toolkit so that it may be used within that software and disseminated publicly.

Important new markets in the implementation of fuel cell electric vehicles contain many different tunnels, especially in urban areas on the east coast of the United States. These tunnels are each owned independently, making regulation and approval potentially different in each. Importantly, many different tunnels contain different factors (traffic pattern, method of construction, size, ventilation, etc.) that means a similar incident could behave differently in different tunnels. Already discussions between Sandia, the Fuel Cell Technologies Office, and the Federal Highway Administration have led to the drafting of a white paper on alternative fuel vehicles, with a review of hazards and research specific to each. A more thorough risk analysis with uncertainty quantification has been done on a vehicle crash in tunnels, and a jet fire was identified as the most likely outcome. However, due to the different varieties of tunnels, a jet fire may behave differently in different tunnels. A group of stakeholders and tunnel owners will be engaged to identify safety assessment gaps and specific concerns that may impact specific tunnels.

Hydrogen can provide clean and efficient propulsion for rail transportation. As in other applications, safety is a primary concern for the various stakeholders in a rail application. Research is needed to identify safety standards and regulations applicable to storage of hydrogen for rail applications, both on the locomotive or tender car as well as stationary fueling infrastructure. This work will identify, collect, and summarize relevant domestic and global codes, standards, and regulations with applicability for storing and using hydrogen as a locomotive fuel. Best practices and lessons learned from existing end users of hydrogen in the heavy-duty sector both for transportation and stationary applications also will be reviewed and discussed.

## FY 2019 PUBLICATIONS/PRESENTATIONS


1. B.D. Ehrhart, "Hydrogen Risk Assessment Models (HyRAM) Overview," presented to Nikola Motors, December 13, 2018.
2. B.D. Ehrhart and A.B. Muna, *Identification of Hydrogen Material Risk Research Areas*, Sandia National Laboratories Report (April 2019), SAND2019-4458.
3. A.B. Muna, "Hydrogen Quantitative Risk Assessment," presented at meeting with Korea Gas Safety, Livermore, CA, June 18, 2019, SAND2019-6572PE.
4. C.B. LaFleur, B.D. Ehrhart, A.B. Muna, and D.M. Brooks, "Tunnel Scenario Estimation and Discussion," presented at Codes & Standards Tech Team Meeting, July 11, 2019, SAND2019-7907PE.
5. G. Feliciano Morales, B.D. Ehrhart, and A.B. Muna, *HyRAM 2.0 User Guide*, Sandia National Laboratories Report (July 2019), SAND2019-8940.
6. B.D. Ehrhart, "Overview and Development of Hydrogen Risk Assessment Models (HyRAM)," presented via web meeting at National Renewable Energy Laboratory, August 2019, SAND2019-9332PE.
7. B.D. Ehrhart, D.M. Brooks, A.B. Muna, and C.B. LaFleur, "Risk Assessment of Hydrogen Fuel Cell Electric Vehicles in Tunnels," *Fire Technology* (2019), https://doi.org/10.1007/s10694-019-00910-z.