Hydrogen Quantitative Risk Assessment

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Project Start Date: October 1, 2003
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) 2018 Objectives

- Develop additional QRA capability to enable HyRAM to be applied to a larger variety of hydrogen applications.
- Update National Fire Protection Association (NFPA) 55/2 gaseous separation distances using scientific justification for risk criteria.
- Provide the necessary information to authorities in the Northeast Corridor to determine whether fuel cell electric vehicles (FCEVs) will be permitted in tunnels.
- Leverage foundational R&D capabilities in QRA and materials to characterize and calculate risk associated with a key hydrogen infrastructure gap (storage).

Technical Barriers

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

(A) Safety Data and Information: Limited Access and Availability

(F) Enabling National and International Markets Requiring consistent RCS

(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 Hydrogen Safety, Codes and Standards Milestones

This project will contribute to achievement of the following DOE milestones from the Hydrogen Safety, Codes and Standards section of the FCTO 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)

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

- 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)
- 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 2018 Accomplishments

- Published report documenting a Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study, which provided a scientific basis for allowing FCEVs in tunnels. The report is intended to enable the adoption of FCEVs in the northeast region.
- Completed a draft of HyRAM 2.0, which includes the customization of QRA analysis and which will expand HyRAM capabilities beyond indoor refueling stations.
- Signed a cooperative research and development agreement (CRADA) with FirstElement Fuel to demonstrate a performance-based approach to a hydrogen refueling station design.
- Addressed public comments and proposed edits to gaseous separation distance tables and annex information to the second draft of NFPA 2 and 55 enabling reduced gaseous hydrogen fueling station footprint.

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 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. HyRAM's hydrogen behavior and QRA models 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

Northeast Corridor Tunnel Updates

The need to understand the risks and implications of traffic incidents involving hydrogen fuel cell vehicles in tunnels is becoming important with the increased deployment of these vehicles, particularly in the Northeast Corridor. The goal of this work was to provide the necessary information to authorities having jurisdiction in the Northeast Corridor to determine whether FCEVs will be permitted in tunnels. A risk analysis was performed to capture potential scenarios that could occur in the event of a crash and provide a quantitative calculation for the probability of each scenario. The scenario with the potential for increased consequence due to hydrogen was determined to be an FCEV crash where the thermally-activated pressure relief device activates due to temperatures from an external fire. This scenario was modeled in three different tunnels and the results determined that there may be localized concrete spalling, but no effect to the structure of the tunnels. The risk and modeling analysis was documented in a Sandia report and published in October 2017. A briefing on the analysis and results was given to the New York and New Jersey Port Authority and Massachusetts Department of Transportation engineers.

Chris LaFleur and DOE/FCTO staff met with Bill Bergeson of the Federal Highway Administration as well as staff from the National Highway Traffic Safety Administration (NHTSA) who have been working with fuel cell vehicles for many years to discuss FCEVs and tunnels. The path forward discussed was to create a comprehensive alternative fuel vehicle tunnel safety roadmap that will collect and address all stakeholders' concerns. This roadmap will include light-, medium-, and heavy-duty vehicles powered by hydrogen fuel cells, compressed natural gas, propane, and advanced chemistry batteries. Sandia will draft an outline for this roadmap in FY 2019, and FCTO and the Federal Highway Administration (FHWA) will form a stakeholder group to collect and address all concerns. This effort will also involve other Office of Energy Efficiency and Renewable Energy offices, such as the Vehicle Technologies Office, as well as NHTSA. The combined federal effort will allow forward progress, with public safety as a priority. Chris LaFleur also led the International Partnership for Hydrogen and Fuel Cells in the Economy Regulations Codes Standards & Safety working group meeting on tunnels in conjunction with the Research Priorities Workshop at the Health and Safety Laboratory in Buxton, United Kingdom, in September.

HyRAM 2.0 Updates

The HyRAM toolkit integrates state-of-the-art models and data for assessing hydrogen safety. HyRAM provides a common platform for stakeholders conducting quantitative risk assessment and consequence analysis for hydrogen systems. The resulting information provides the scientific basis to ensure code requirements are consistent, logical, and defensible.

In FY 2018, the HyRAM development team focused their efforts on developing a customizable QRA analysis to expand HyRAM's analysis capabilities beyond an indoor refueling station. The team determined that the best way to accomplish this goal was not to integrate an existing event/fault tree software but instead leverage the plethora of free, publicly available fault tree software and provide a method for the user to enter in the risk results. To accomplish this, updates to the QRA source code were made, including the conversion of this part of the software from C# to Python. The graphical user interface text and images have been updated to display the new QRA options. Figure 1 illustrates the updated image that will be inserted into HyRAM showing the editable potions of the analysis.

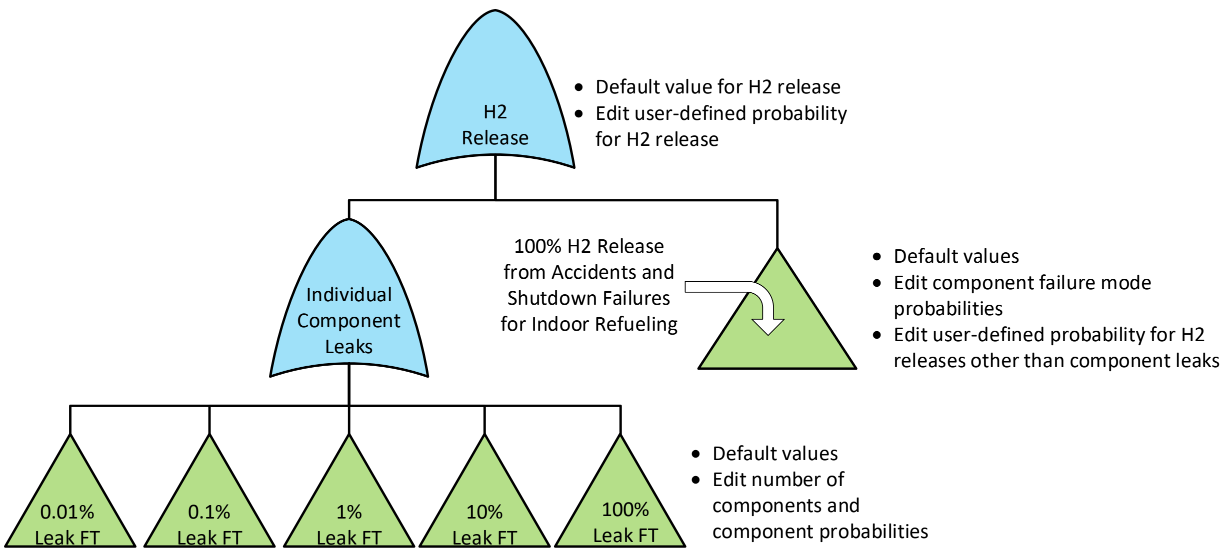

Figure 1. Updated HyRAM fault tree showing editable portions of the QRA

The HyRAM QRA analysis has also been updated to include two new generic components. The intent of this update is that systems with a unique component would be able to enter in reliability data for their component and that would be added to the existing QRA framework. A component failures table in HyRAM is used to compute the accidental and shutdown failure parameters for the 100% leak release calculation only (and not in the other four fault trees with other leak sizes). This table has been updated so a user can edit the distribution type and parameters, as needed. A new tab has been added that displays the distributions for user ease of use. The scenario stats (output of QRA calculation) have also been updated in HyRAM. First, the scenario rankings have added a branch line probability to ease in the creation of an event tree, if needed. Additional significant digits were added to provide for more clarity in the average number of events per year and the potential loss of life (PLL) contribution calculations. The cut sets were also edited for clarity and ease. Instead of listing only the 100% leak cut sets, there are now five tables, corresponding to the five fault trees, with each cut set probability listed. The interface between the C# and the Python was also edited to directly pass the C# inputs into Python without converting them into a text file as an intermediate. This updated framework runs faster and will reduce errors.

The HyRAM QRA updates are currently in test form and will be debugged in Q1 of FY 2019. The goal is that HyRAM 2.0 will be re-issued a copyright and be available for release in FY 2019. The HyRAM team also published SAND2018-0749, titled "HyRAM V1.1 User Guide." This document captures the main features of HyRAM version 1.1 and is based upon the HyRAM V1.0 User Guide.

Real-World Application of Alternate Means

Sandia executed an in-kind CRADA with FirstElement Fuel on March 14, 2018. The statement of work for this CRADA is to develop a performance-based design for a hydrogen refueling station, utilizing Sandia's QRA methodology. The first task for this CRADA is to collaborate to prepare station permitting documents and submit to an applicable authority having jurisdiction for approval. The second task is to develop a final report documenting the technical results/accomplishments for the project. FirstElement Fuel has 19 planned liquid-hydrogen-based refueling stations and work has begun to develop calculations to support an alternate means justification to challenge separation distances. This justification will be presented to an authority having jurisdiction.

NFPA 2/55 Technical Committee Support

Sandia has worked closely with the NFPA 2 and 55 technical committees and task groups to update the gaseous storage separation distances based on a risk-informed process. In FY 2018, the public comments submitted to NFPA 2 and 55 were reviewed and necessary changes were identified in the code. Public comments were submitted to fix the errors. Sandia attended the second draft of NFPA 2 and 55 technical committee meetings to vote on public comments as members of the committees. All of Sandia's public comments were accepted in both NFPA 2 and 55, which included the following: fixing errors within the separation distance table calculations, correcting annex material to reflect the same information in both NFPA 2 and 55, and updating the history of the risk-informed approach taken to derive separation distances.

CONCLUSIONS AND UPCOMING ACTIVITIES

Sandia will continue to provide information to authorities and other interested parties on our tunnel analysis. In addition, Sandia will work on developing a tunnel safety roadmap for light-, medium-, and heavy-duty vehicles powered by hydrogen fuel cells, compressed natural gas, propane, and advanced chemistry batteries. This work will be in conjunction with a combined federal effort from DOE FCTO, DOE Vehicle Technologies Office, NHTSA, and FHWA.

The HyRAM toolkit provides a platform with state-of-the-art hydrogen models for assessing the risk of hydrogen systems and the consequences of hydrogen releases and fires to enable industry-led analyses. We plan to add modules for consequence modeling, including the ability to calculate the physical effects of liquid hydrogen releases, cold plumes, and subsequent ignitions, pending the results from Sandia's liquid hydrogen experiments and modeling.

FY 2018 PUBLICATIONS/PRESENTATIONS

1. C.B. LaFleur, G.A. Bran Anleu, A.B. Muna, B.D. Ehrhart, M.L. Blaylock, W.G. Houf. "Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study." Sandia National Laboratories, October 2017. SAND2017-11157.
2. C.B. LaFleur. "Hydrogen Fuel Cell Tunnel Analysis." Presented to Massachusetts Department of Transportation Engineers, October 20, 2017. SAND2017-8177 O.
3. A. Muna. "Hydrogen Quantitative Risk Assessment 2017 Update and Path Forward." Presented at US DRIVE Hydrogen Codes & Standards Tech Team Meeting, October 12, 2017.
4. A.B. Muna. "QRA and Physics Mode Flow Charts." SAND2017-11836.
5. A.B. Muna. "Hydrogen Quantitative Risk Assessment 2017 Update and Path Forward." Presented at Codes and Standards Technical Team Meeting, October 12, 2017. SAND2017-10867 PE.
6. A.B. Muna. "Hydrogen Quantitative Risk Assessment." Presented at meeting with KGS and Hoseo University in Long Beach, CA, November 6–7, 2017. SAND2017-11689 PE.

7. A.B. Muna. "Hydrogen Quantitative Risk Assessment Path Forward." Presented at meeting with KGS and Hoseo University in Long Beach, CA, November 6–7, 2017. SAND2017-11690 PE.
8. E.A. Sena, B.D. Ehrhart, A.B. Muna. "HyRAM 1.1 User Guide." Sandia National Laboratories, January 2018. SAND2018-0749.
9. B.D. Ehrhart. "Hydrogen Risk Assessment Models (HyRAM) Overview." Virtually presented at the HySA Hydrogen Safety Awareness Meeting, University of the Western Cape, South Africa. May 25, 2018. SAND2018-5511 PE.
10. G.A. Bran-Anleu. "Quantitative Risk Analysis to Guide Station Design." Presented at the International Infrastructure Workshop, September 11, 2018.
11. C.B. LaFleur. "Hydrogen Fuel Cell Tunnel Analysis." Presented at the IPHE Regulations Codes Standards & Safety working group meeting, September 18, 2018. SAND2017-8177 O.