VIII.5 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) 2017 Objectives

- Review/update HyRAM to include overpressure, layer, gas plume models and Engineering Toolkit in version releasable to the public.
- Develop a research plan to address the next phase of the risk task that will include the intersection of materials research and QRA to address an industry barrier.

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.

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

(F) Enabling national and international markets requiring consistent RCS

(G) Insufficient technical data to revise standards

Contribution to Achievement of DOE Safety, Codes & Standards Milestones

This project will contribute to achievement of the following DOE milestones from the 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)
- 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 2017 Accomplishments

- Publically released the HyRAM 1.1 software for risk analysis of hydrogen infrastructure systems.
- Improved existing HyRAM capabilities to include reduced computing time, and fixed critical issues, in addition to quality assurance testing.
- Expanded HyRAM capabilities by adding new models, such as three-dimensional positioning for flame targets, improved flame model, updated heat flux radiation model, and a TNT Mass Equivalence calculator.
- Published a SAND Report which identifies and evaluates research areas in hydrogen materials where QRA could be used to address a barrier to the progress of the hydrogen fuel cell industry. The areas with the most promise were stress rupture of composite pressure vessel, polymer failure modes and mechanisms in high

pressure hydrogen, and initial crack distribution in metallic pressure vessels.

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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. 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

HyRAM 1.1 Updates

Code committees and industry are both interested in using QRA and behavior modeling to enable code development and code compliance for hydrogen systems. Gaps and limited availability of data, models and tools relevant to hydrogen infrastructure systems form a barrier to this goal. This core research activity addresses this gap by developing and releasing HyRAM, an innovative software tool that integrates QRA and physical models of hydrogen behavior and consequences. HyRAM reduces industry burden and allows hydrogen safety experts to focus on obtaining safety insights rather than creating, validating, and documenting risk assessment algorithms and physical models.

The HyRAM package will enable installation designers and code and standards development organizations to conduct consequence modeling and QRA with state-of-the-art, validated science and engineering models. HyRAM formalizes the tools and methods which have been developed by Sandia through multiple Fuel Cell Technologies Office projects. HyRAM development began in FY 2014. In FY 2015 we issued a prototype HyRAM (V1.0alpha) to selected stakeholders with limitations on its use. During FY 2016 we revised the HyRAM copyright to make HyRAM 1.0 available for free download.

In February 2017, we released HyRAM 1.1 via http://hyram.sandia.gov, which reflects multiple new modules, significant testing and quality assurance activities. HyRAM 1.1 includes fixes to 10 major and several minor code defects as well as improved code readability and international compatibility. Issues with workspace load/save feature across versions, jet flame plot truncation and fonts issue, stability/proper execution issue in Engineering Toolkit, Windows 10 compatibility issue were also corrected. Features such as extended workspace save/load functionality, user-selectable Python language, 3-dimensional positioning input to H2-Flame input, improved flame model, updated XRad model, and TNT Mass Equivalence calculation were added. The updated version achieves a 67% reduction in computing time, with QRA mode now running in approximately 2.5 min with the curved flame model. We communicated the availability of HyRAM 1.1 to current users. Along with this release, we also published a revised SAND report documenting the algorithms of HyRAM 1.1.

We continue to see a steady number of downloads of HyRAM due to the many stakeholder interactions and external presentations. The comparison between October 2016 (first six months of HyRAM 1.0) and the second six months of HyRAM release is shown in Table 1. Users come from a wide range of stakeholder types, including multiple users from U.S. and international national labs, regulators, and universities, small businesses, and large multi-national gas suppliers, manufacturers, and consultants. In FY 2017 we added users from Greenlight Innovation (CA), Tongji University (CH), Telemark University and Safety & Risk Management Group (Denmark), VTT (FI), Ineris and Neodyme (FR), HPS Gmbh, Indian Oil R&D, Kawasaki Heavy Indsutries (JP), SynergenOG (Malaysia), KGS (KA), HNTB, Air Liquide, Hornblower, International Energy Association, National Renewable Energy Laboratory, Plug

Power, Pacific Northwest National Laboratory, and SNL (USA) and other users from Saudi Arabia and China. The increasing number of users provides evidence of direct value to the community.

TABLE 1. HyRAM Download and User Tracking Metrics

	March–October 2016	October 2016–March 2017
	HyRAM 1.0	HyRAM 1.1
Countries	20	20
Downloads	100 +	137
Licensed Users	55	77

During FY 2017, the commercialization of HyRAM was evaluated. It was concluded that the licensing of HyRAM 1.1 in its current form is limited and would not achieve the goal of generating sufficient funds to support maintenance and further development in the next FY. Currently, the fault trees feeding the QRA calculations in HyRAM are based on retail hydrogen refueling stations. Many of the users for whom this application is of interest already took advantage of the free download of HyRAM. However, HyRAM could be marketed to a broader customer base with the following two capabilities. First, the integration of risk software (targeting IRIS which was developed previously for the Federal Aviation Administration at University of Maryland) would enable the user to edit the fault trees so the QRA calculation can be adapted to a broader range of applications, including grid-scale applications. Initial efforts regarding the feasibility of integrating IRIS into HyRAM were explored in FY 2017. Second, adapting HyRAM to other alternate fuels, namely compressed natural gas and propane, would also increase the number of potential customers. This feature could be completed through a cooperative research and development agreement with South Korea researchers who have already been awarded funding for this effort.

QRA and Material Risk

Sandia possesses core capabilities in hydrogen research, including hydrogen QRA, hydrogen behavior, and hydrogen materials. These interrelated activities are enabled by a set of differentiating capabilities, including the HyRAM software tool for QRA and consequence modeling, and the Turbulent Combustion Laboratory, which enables lab-scale experiments into the behavior of hydrogen under a wide range of controlled conditions. The objective of this research is to capitalize on SNL's capabilities in hydrogen materials and QRA to address a barrier to the progress of the hydrogen fuel cell industry. In particular, this research plans to quantify the risk of materials for pressure vessel failure and identify a path forward to characterizing the calculation of this risk. This research will provide a better understanding of pressure vessel failure to cylinder manufacturers, the hydrogen fuel cell safety community and other applications.

Hydrogen storage technologies are a key part of hydrogen infrastructure for transportation and have implications for large scale problems. A key scientific question is determining how to account for material properties with a QRA framework. Sandia has developed a framework for predicting overall risk of the system from knowledge of reliability of various components such as storage tanks. However, we have little data to predict reliability of components, such as composite storage vessels. Without data it is necessary to use knowledge of material properties, defects, and design elements to predict the reliability and risk. There is currently little understanding of how the distribution of defects affects the ultimate performance of components, like storage tanks.

Progress was made on the new tasking focused on developing a vision for leveraging the fundamental research of SNL's core competencies in QRA and materials science to identify and address a barrier, such as pressure vessel reliability. Multiple issues were identified where materials research could potentially benefit from QRA. Each of these issues were researched further and documented into a SAND report. The SAND report will be completed in FY 2017 and includes a suggested path forward for future research activities in materials risk.

CONCLUSIONS AND UPCOMING ACTIVITIES

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. However, additional challenges remain within codes and standards, including the development of defensible separation distances for liquid hydrogen stations and need for additional data for QRA. 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 SNL's liquid hydrogen experiments and modeling. Existing HyRAM models (e.g., the gas plume model) will be kept current as scientific consensus changes. We plan to expand the capabilities of the QRA algorithm to support modeling of additional scenarios as well as features to enable more detailed insight into system reliability.

Applying QRA concepts to pressure vessel reliability analysis can ideally create a framework that can be broadened beyond cylinders. Similarly, using these approaches will create new pressure vessel data that can be used within a QRA framework as part of system-level safety assessment. Addressing the root causes of hydrogen release will impact every application of hydrogen as an energy solution. Any system that uses hydrogen, from large grid scale application such as those proposed in H2@Scale to an individual hydrogen vehicle refueling station require hydrogen storage of various sizes. Our work in determining how to account for material properties within a QRA framework will provide a better understanding of pressure vessel failure and support the hydrogen fuel cell safety community.

FY 2017 PUBLICATIONS/PRESENTATIONS

1. Software: HyRAM 1.1. Issued February 2017. Software available at http://hyram.sandia.gov.

2. K.M. Groth, E.S. Hecht, J.T. Reynolds, M.L. Blaylock, E.E. Carrier. Methodology for assessing the safety of Hydrogen Systems: HyRAM 1.1 technical reference manual. SAND2017-2998.

3. K. Groth. "SCS011: Hydrogen Quantitative Risk Assessment" at DOE FCTO Hydrogen Program Annual Merit Review, Washington DC, June 6, 2017.

4. K. Groth. "Hydrogen QRA & HyRAM: 2016 in review." US DRIVE H2 Codes & Standards Tech Team Meeting, October 13, 2016.

5. K. Groth (invited presentation). "Enabling hydrogen safety, codes, and standards through Quantitative Risk Assessment." George Mason University Physics Colloquium, Fairfax, VA, November 4, 2016.

6. K. Groth. "Hydrogen QRA & HyRAM: Status and next directions." Presented at the IEA HIA Hydrogen Safety Task 37 Meeting, Bethesda, MD, November 28, 2016.

7. K. Groth (invited panelist). "Managing safety risk in new energy technologies." Reliability & Maintainability Symposium (RAMS) in Orlando, FL. January 24, 2017. SAND2017-0260 C.