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) 2016 Objectives

- Extend HyRAM modules for simulating gas plume, overpressure, and laying behavior to enable their use in safety assessment for hydrogen fueling infrastructure.
- Make an unsupported research version of HyRAM available for free download by national and international stakeholders.
- Facilitate use of HyRAM by publishing documentation, engaging with stakeholders.

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 Requires Consistent RCS

(G) Insufficient Technical Data to Revise Standards

(L) Usage and Access Restrictions

Contribution to Achievement of DOE Safety, Codes & Standards 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)
- 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 2016 Accomplishments

- Publicly released a free version of HyRAM V1.0 software for risk analysis of hydrogen infrastructure systems.
- Expanded HyRAM capabilities to include modules for simulating gas plume dispersion, overpressure, and layering behavior from user-defined releases. Added an Engineering Toolkit to facilitate simple hydrogen safety calculations, including thermodynamic conversions and mass flow rate calculations.
- Published a technical reference manual documenting the methodology and models used in HyRAM V1.0. Published a user guide for the HyRAM V1.0 software.

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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

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.

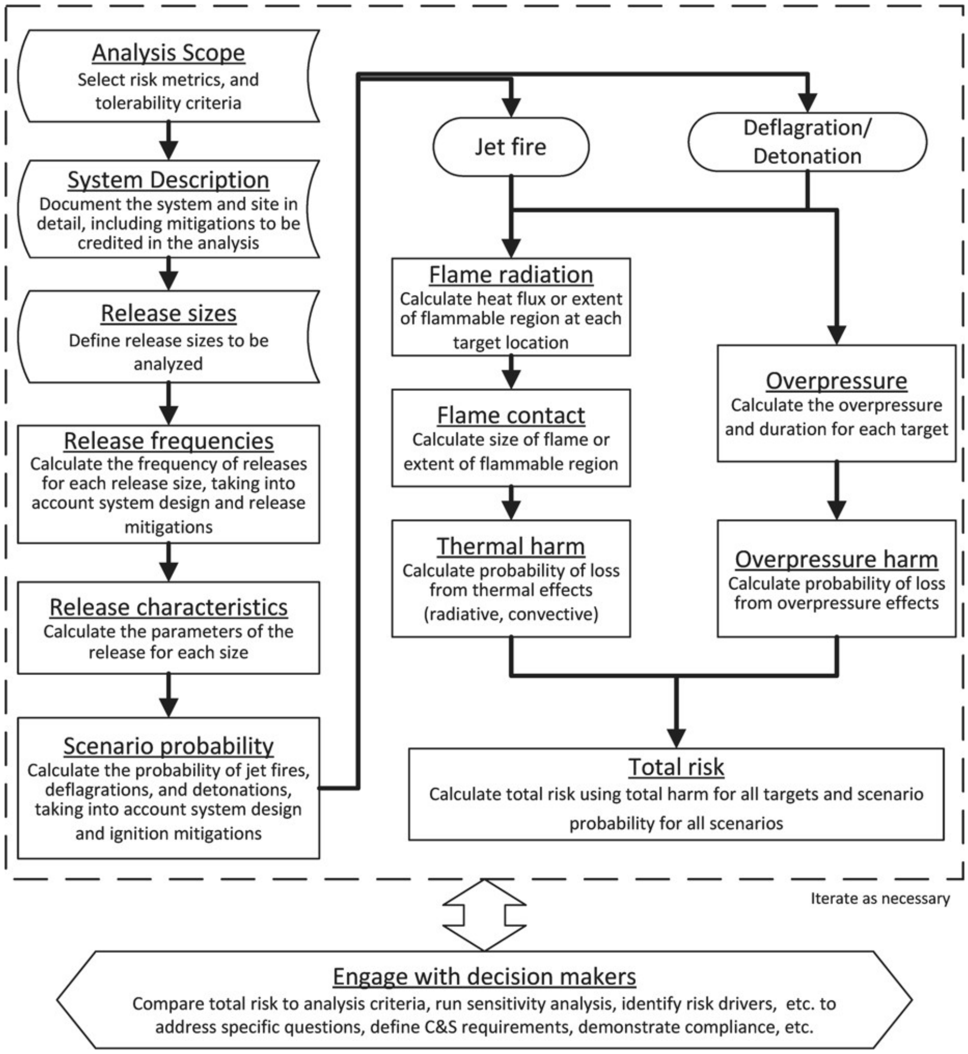
The HyRAM package will enable installation designers and code and standards development organizations to conduct consequence modeling and QRA with state-of-the-art, validated science and engineering models (see Figure 1). HyRAM formalizes the tools and methods which have been developed by Sandia through 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 significantly increased the functionality of HyRAM and we also revised the HyRAM copyright to make HyRAM available for use by anyone. HyRAM is available for free download at http://hyram.sandia.gov; the current version is 1.0.1. HyRAM now has click-to-accept license terms, which relax the usage restrictions from prior releases and requires users to acknowledge the limitations of this research software.

A new key feature is a model and user interface for hydrogen gas plume dispersion; sample results are shown in Figure 2. The new gas plume model is based on the experimental work completed in 2015 in Sandia's Turbulent Combustion Laboratory. We also completed a module which allows users to calculate two behaviors of hydrogen within an enclosure: overpressure (for ignited hydrogen release) and layering/accumulation behavior (for unignited hydrogen releases). HyRAM now uses the stable overpressure model from the fourth quarter of FY 2015, which resolved discrepancies with expected results. This HyRAM module allows the user to visualize the time-dependent hydrogen accumulation and to calculate and plot peak overpressure given different ignition times (Figure 3). We also added an Engineering Toolkit, which allows users to perform additional calculations relevant to hydrogen systems. Currently the Engineering Toolkit includes tank volume-to-mass conversion, calculation of a release rate (steady-state or blowdown), and density, temperature, and pressure conversion.

A major thrust for the year included working with external stakeholders to obtain feedback about usability and functionality. We created 29 HyRAM versions (23 internal test versions, four alpha releases, and two public releases). We partnered with eight external stakeholders who provided feedback on HyRAM V1.0alpha. We presented HyRAM in numerous national and international forums (see presentations list). We used this stakeholder feedback to focus our software improvements, including the new features and streamlined input and output windows.

We also completed important HyRAM documentation, including the technical reference manual and multiple reports and papers documenting for HyRAM V1.0 (see list of



C&S – Codes and standards

FIGURE 1. Summary of QRA methodology implemented in HyRAM

publications). This documentation provides traceability and enables verification and validation of the HyRAM algorithm, models, approach, assumptions, and information sources.

HyRAM is actively being used for codes and standards development by the NFPA 2 and ISO Technical Specification TS-19880-1, both for risk-informed code development and for risk-informed code compliance (e.g., performance-based design). During FY 2016, HyRAM was used extensively by ISO Technical Committee (TC) 197 WG24 in the development of ISO TS-19880-1. The safety assessment methodology in TS-19980-1, which is based on the HyRAM methodology, allows countries to follow a common methodology for performing safety assessment with county- or region-specific assumptions and modeling choices. HyRAM was used to support the development of regional examples contained in Annex A. HyRAM provides a means for rapidly evaluating different examples, which helped the committee overcome significant barriers to an international consensus.

During FY 2016 HyRAM was used to support performance-based designs for hydrogen fueling stations within NFPA 2. HyRAM was used to calculate baseline risk metrics for a generic station and to provide a platform for industry to compare specific design proposals to that baseline (see [1] on publication list). HyRAM is also being used to explore liquid separation distances for NFPA 2.

HyRAM could be used to support the establishment of safety distances and other mitigation credits, and furthermore can be used to enable a performance-based compliance option within these codes and standards. Longer-term, HyRAM is anticipated to support development of safety cases and design decisions for user-defined hydrogen installations, and can also be used to demonstrate improvements in facility safety.

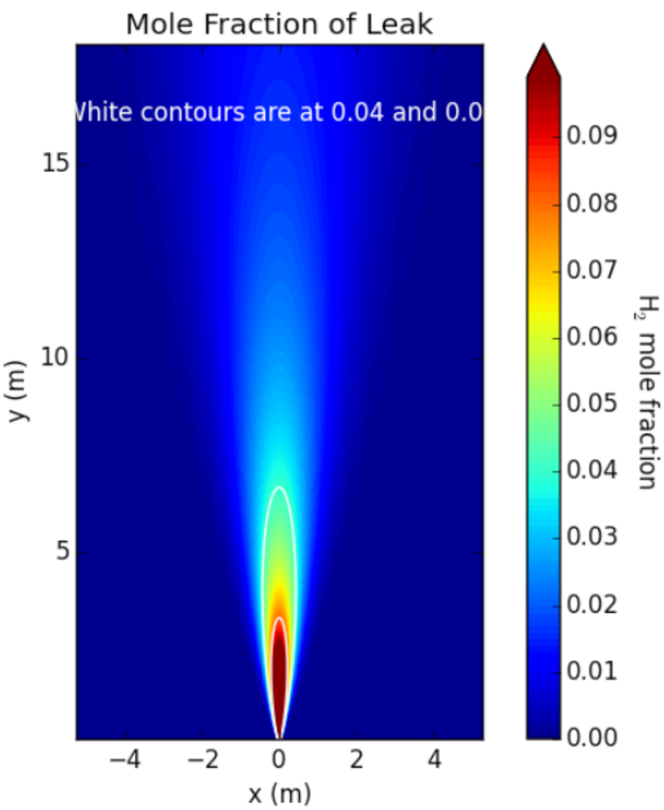


FIGURE 2. Output from new HyRAM feature to calculate the mole fraction of release from a user-defined leak. The white contours outline the edges of user-specified concentrations (in this image, the 4% and 8% contours are displayed).

CONCLUSIONS AND FUTURE DIRECTIONS

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. During FY 2016 we used HyRAM to revise important requirements in both NFPA 2 and ISO TS-19880-1, thereby reducing barriers to hydrogen infrastructure deployment. However, additional challenges remain within both codes, including the development of defensible separation distances for liquid hydrogen stations and need for additional data for QRA.

HyRAM development activities are focused on adding capabilities necessary to inform near-term regulations, codes, and standards needs, including those from NFPA 2 and ISO TS-19880-1. There are several important scientific gaps that must be addressed including: a need for validated models of liquid hydrogen behavior and an ongoing need for data about hydrogen system failures, hydrogen component reliability (and failures), and mitigation effectiveness. There is also a need to extend HyRAM to address a wider variety of hydrogen infrastructure systems, including containerized systems and new types of infrastructure.

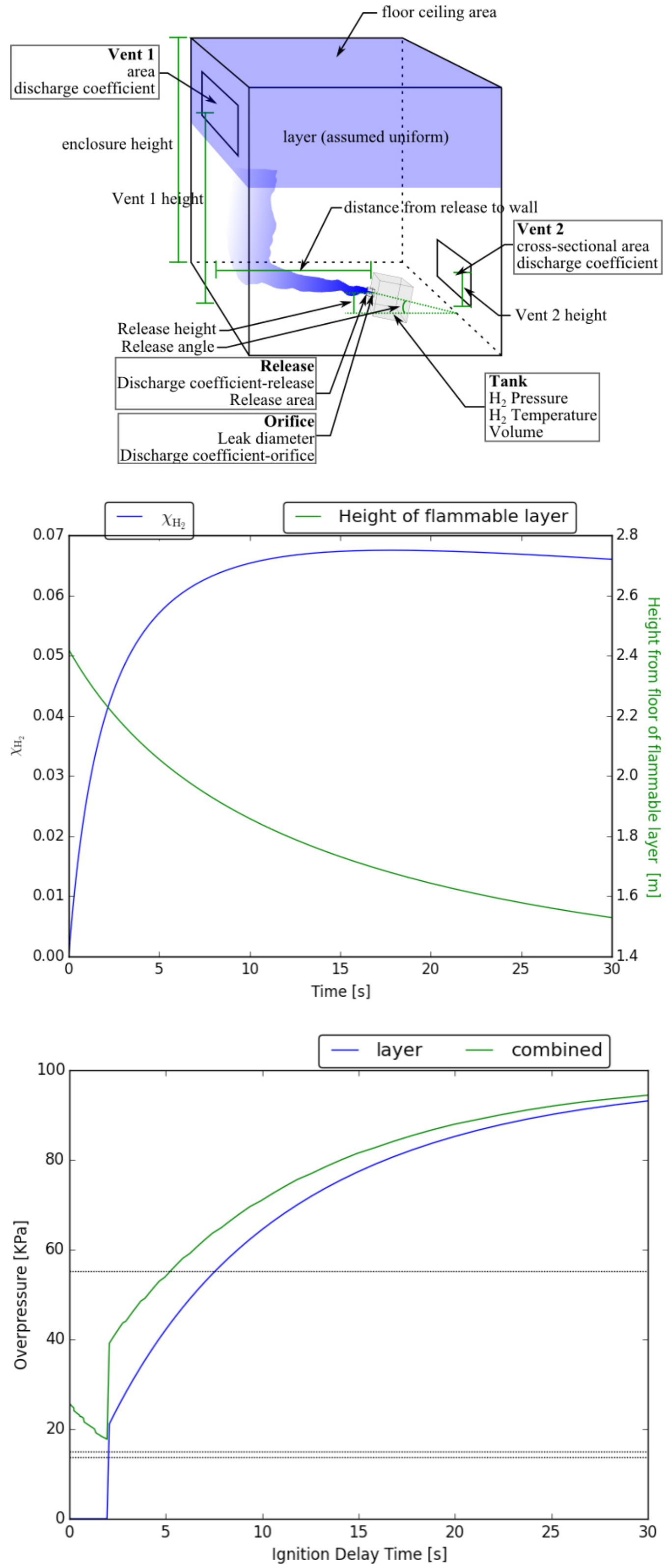


FIGURE 3. New HyRAM overpressure module, including illustrate of required used input (top), and output graphs of peak overpressure at different ignition times (bottom) and height of the flammable hydrogen layer within the enclosure (center)

The flexible architecture of the HyRAM framework enables the incorporation of additional features including both physical models and QRA capabilities. 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. We will also add new physics-based modules for calculating hydrogen ignition probability. Existing HyRAM models (e.g. the gas plume model) will be kept current as scientific consensus changes. We will 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.

We will design a set of HyRAM example cases which will facilitate testing and verification of the modules by users. HyRAM will continue to be a research prototype; external partners are needed to support formal software development activities.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. *Robert Schefer Memorial Best Paper Award.* Presented to Katrina Groth and Ethan Hecht at the International Conference on Hydrogen Safety (ICHS) for "HyRAM: A methodology and toolkit for QRA of hydrogen systems." Tokyo, Japan, October 2015.

2. *2016 DOE Hydrogen and Fuel Cells Program R&D Award* (Safety, Codes, and Standards program). Presented to Katrina Groth for "outstanding leadership and technical contribution to hydrogen safety and risk assessment." Washington, DC, June 2016.

3. Copyright: HyRAM (Hydrogen Risk Assessment Models) v. 1.0. February 17, 2016.

FY 2016 PUBLICATIONS/PRESENTATIONS

1. A.C. LaFleur, A.B. Muna, and K.M. Groth. *Fire Protection Engineering Design Brief Template: Hydrogen Refueling Station*, SAND2015-4500, Sandia National Laboratories, June 2015.

2. Hannah R. Zumwalt and Katrina M. Groth. *HyRAM V1.0 User's Manual.* SAND2015-7380 R, Sandia National Laboratories, Albuquerque, NM, August 2015.

3. K.M. Groth and E.S. Hecht. "HyRAM: A methodology and toolkit for Quantitative Risk Assessment of Hydrogen Systems." *In Proceedings of the International Conference on Hydrogen Safety (ICHS 2015),* Yokohama, Japan, October 19–21, 2015.

4. A.C. LaFleur, A.B. Muna and K.M. Groth. "Application of Quantitative Risk Assessment for Performance-Based Permitting of Hydrogen Fueling Stations." *In Proceedings of the International Conference on Hydrogen Safety (ICHS 2015)*, Yokohama, Japan, October 19–21, 2015.

5. T. Skjold, D. Siccama, H. Hisken, A. Brambilla, P. Middha, K.M. Groth and A.C. LaFleur. "3D Risk management for hydrogen installations (Hy3DRM)." *In Proceedings of the International Conference on Hydrogen Safety (ICHS 2015),* Yokohama, Japan, October 19–21, 2015.

6. J. Schneider, G. Dang-Nhu, N. Hart and K. Groth. "ISO 19880-1, Hydrogen Fueling Station and Vehicle Interface Safety Guideline." *In Proceedings of the International Conference on Hydrogen Safety (ICHS 2015),* Yokohama, Japan, October 19–21, 2015.

7. C. San Marchi, E.S. Hecht, I.W. Ekoto, K.M. Groth, C. LaFleur, B.P. Someday, R. Mukundan, and T. Rockward. Advances in research and development to enhance the scientific basis for hydrogen regulations, codes, and standards. In Proceedings of the International Conference on Hydrogen Safety (ICHS 2015), Yokohama, Japan, October 19–21, 2015.

8. K.M. Groth. "HyRAM: A methodology and toolkit for QRA of hydrogen systems." Presented at the International Conference on Hydrogen Safety (ICHS 2015), Yokohama, Japan, October 21, 2015.

9. K.M. Groth. "Application of quantitative risk assessment for performance-based permitting of hydrogen fueling stations." Presented at the International Conference on Hydrogen Safety (ICHS 2015), Yokohama, Japan, October 21, 2015.

10. K.M. Groth. "H2 safety integration toolkits: HyRAM Version 1.0." Presented at the IEA HIA Hydrogen Safety Task 37 Meeting, Tokyo, Japan, October 23, 2015.

1.1 K.M. Groth. "A brief intro to Human Reliability Analysis." Presented at the IEA HIA Hydrogen Safety Task 37 Meeting, Tokyo, Japan, October 23, 2015.

12. K. Groth. "Safety assessment & mitigation sub-team update." Presented at ISO TC197 WG24 meeting, Tokyo, Japan, October 27, 2015.

13. Katrina M. Groth, Ethan S. Hecht and John T. Reynolds. *Methodology for assessing the safety of Hydrogen Systems: HyRAM 1.0 technical reference manual*. SAND2015-10216, Sandia National Laboratories, Albuquerque, NM, November, 2015.

14. Katrina M. Groth. "HyRAM: A methodology and toolkit for hydrogen QRA & behavior modeling." Presentation to US DRIVE - H2 Codes & Standards Tech Team, November 12, 2015.

15. Hydrogen Risk Assessment Model (HyRAM) website. http://hyram.sandia.gov First published January 2016.

16. C. San Marchi, E.S. Hecht, I.W. Ekoto, K.M. Groth, C. LaFleur, B.P. Someday, R. Mukundan, T. Rockward, J. Keller & C.W. James. "Overview of the DOE hydrogen safety, codes and standards program, part 3: Advances in Research and Development to Enhance the Scientific Basis for Hydrogen regulations, Codes and Standards." *Submitted for publication in International Journal of Hydrogen Energy,* (Submitted Feb 2016).

17. Katrina M. Groth, Hannah R. Zumwalt, Andrew Clark. *HyRAM V1.0 User Guide*. Sandia National Laboratories, Albuquerque, NM, March 2016.

18. Jay Keller, Laura Hill, Kristian Kiuru, Katrina Groth, Ethan Hecht, Will James, and Thomas Jordan. HySafe research priorities workshop report. Sandia National Laboratories, Albuquerque, NM, SAND2016-2644, 2016.

19. Katrina M. Groth (presentation). "Overview of HyRAM (Hydrogen Risk Assessment Models) Software for Science-Based Safety, Codes, and Standards." U.S. Department of Energy Fuel Cell Technologies Office webinar series, April

26, 2016. Archived version available at http://energy.gov/eere/fuelcells/2016-webinar-archives.

20. K. Groth. "SCS011: Hydrogen Quantitative Risk Assessment." Presented at DOE FCTO Hydrogen Program Annual Merit Review, Washington, DC, June 7, 2016.

21. K. Groth. "Safety assessment & mitigation sub-team update." Presented at ISO TC197 WG24, Munich, Germany, 22 June 2016.

22. Katrina M. Groth & Ethan S. Hecht. "HyRAM: A methodology and toolkit for Quantitative Risk Assessment of hydrogen systems." Accepted for publication in International Journal of Hydrogen Energy (Accepted July 2016).