DOE annual report FY14

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R&D for Safety, Codes and Standards: Materials and Components Compatibility

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DOE Manager: (will be supplied – no input required)

Project Start Date: October 1, 2003
Project End Date: Project continuation and direction determined annually by DOE

Overall Objectives

- Optimize the reliability and efficiency of test methods for structural materials and components in hydrogen gas
- Generate critical hydrogen compatibility data for structural materials to enable technology deployment
- Create and maintain information resources such as the "Technical Reference for Hydrogen Compatibility of Materials"
- Demonstrate leadership in the international harmonization of standards for qualifying materials and components for high-pressure hydrogen service

Fiscal Year (FY) 2014 Objectives

- Demonstrate fatigue life measurements in gaseous hydrogen
- Determine boundary conditions for hosting "open-source" database of materials and materials properties in gaseous hydrogen
- Complete integration of automated gas-distribution manifold; establish cost estimates for variable-temperature testing hardware
- Foster growth of international collaboration and leadership on materials science of hydrogen embrittlement, in particular within the International Institute for Carbon-Neutral Energy Research (I2CNER)
- Leverage partnership at AIST to supplement fracture testing database to influence materials testing standards; establish roadmap for next phase collaboration with AIST (2015-2018)

Technical Barriers

This project addresses the following technical barriers from section 3.8 of the 2012 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

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 2012 Fuel Cell Technologies Office Multi-Year Research, Development and Demonstration Plan:

- Milestone 2.9: Publish technical basis for optimized design methodologies of hydrogen containment vessels to account appropriately for hydrogen attack (4Q, 2013)
- Milestone 2.16: Demonstrate the use of new high-performance materials for hydrogen applications that are cost-competitive with aluminum alloys. (4Q, 2017)
- Milestone 2.3: Implement validated mechanism-based models for hydrogen attack in materials (4Q 2016)
- Milestone 3.3: Reduce the time required to qualify materials, components, and systems by 50% relative to 2011 with optimized test method development. (1Q 2017)
- Milestone 3.4: Develop hydrogen material qualification guidelines including composite materials (Q4, 2017)
- Milestone 4.8: Completion of the GTR Phase 2. (1Q, 2017)
- Milestone 5.2: Update materials compatibility technical reference (4Q, 2011-2020)
- Milestone 5.4 Develop and publish database for properties of structural materials in hydrogen gas. (2Q, 2013)

FY 2014 Accomplishments

- Completed initial test matrix to measure fatigue life of the stainless steel 21Cr-6Ni-9Mn in 103 MPa hydrogen gas. This testing satisfies the need to quantitatively evaluate methods recently published in the CSA CHMC1 standard and to generate qualification data for lower-cost stainless steels.
- Finalized design requirements and procurement process for the variable-temperature testing in hydrogen gas system.
- Devised plan with international partner AIST to propose test method to ASTM International for performing rising-displacement fracture threshold testing of structural metals in hydrogen gas.

Introduction

A principal challenge to the widespread adoption of hydrogen infrastructure is the lack of quantifiable data on its safety envelope and concerns about additional risk from hydrogen. To convince regulatory officials, local fire marshals, fuel suppliers, and the public at large that hydrogen refueling is safe for consumer use, the risk to personnel and bystanders must be quantified and minimized to an acceptable level. Such a task requires strong confidence in the safety performance of high pressure hydrogen systems. Developing meaningful materials characterization and qualification methodologies in addition to enhancing understanding of performance of materials is critical to eliminating barriers to the development of safe, low-cost, high-performance high-pressure hydrogen systems for the consumer environment.

Approach

The Materials and Components Compatibility project leverages decades of experience in high-pressure hydrogen systems, well-developed industry partnerships, and a core capability in hydrogen-materials interactions anchored by the Hydrogen Effects on Materials Laboratory to focus on three critical activities: 1) optimize materials characterization methodologies, 2) generate critical hydrogen compatibility data for materials to enable technology deployment, and 3) provide international leadership by assembling and maintaining a technical reference that is populated with vetted data and includes a technical assessment of the data and its application.

Results

Fatigue life measurements in gaseous hydrogen

Fatigue life assessment is a common design methodology that has only recently received attention in the context of qualifying materials for hydrogen service. In particular, the revised CHMC1 standard from CSA describes a materials qualification pathway that uses notched fatigue tests to qualify materials for hydrogen service.

Notched fatigue tests in high-pressure gaseous hydrogen were demonstrated at SNL for an austenitic stainless steel, 21Cr-6Ni-9Mn. Testing results (Figure 1) show a significant effect of high-pressure gaseous hydrogen (103 MPa) on the fatigue cycles to failure for nominally the same applied stress cycle. The results are also compared to previous testing in air with a more acute notch showing that the fatigue life in hydrogen is greater than for tests in air with a more acute notch. The significance of these results is not yet clear, as more data is necessary to clarify the trends. In general, the testing has shown that the testing configuration in gaseous hydrogen is feasible and provides basic trends that are consistent with expectation (e.g., power-law like relationship between stress and cycles to failure).

Fatigue life assessment (e.g., using notched tensile fatigue tests) is anticipated to aid the qualification of lower cost materials for generic high-pressure hydrogen service; however, more work is necessary to demonstrate reproducibility and evaluate the effects of notch acuity in these tests. The effect of frequency must also be considered for fatigue testing, but has not been explored in this testing configuration.

"Open-source" database of material properties in gaseous hydrogen
Reliable and searchable materials properties measured in gaseous hydrogen is significant limitation to selection of materials for hydrogen service. To meet this need, SNL is exploring methods to augment the Technical Reference for Hydrogen Compatibility of Materials (http://www.sandia.gov/matlsTechRef/) with a database of materials properties. Sandia, as part of the Material Data Management Consortium (MDMC, Granta-organized industry consortium), has engaged this organization in support of building the schema for incorporation of environmental variables in their database structure with the aim of a comprehensive hydrogen effects in materials database. Discussions with Granta and individuals from MDMC suggest a precedent for data exchange using web-based interface built on Granta MI (Materials Information). Granta is the leader in materials information/database management solutions. Additional discussion is required to quantify the cost of maintaining an open platform for dissemination of materials properties measured in gaseous hydrogen.

System for variable-temperature testing in hydrogen gas
Materials qualification for hydrogen fueling applications requires the measurement of materials properties, especially fatigue properties, in high-pressure gaseous hydrogen and low temperature. It is well known, for example, that certain materials such as austenitic stainless steels are most susceptible to hydrogen embrittlement at temperatures near 233K (-40˚C). Facilities for testing materials under the combined influence of variable temperature and high pressure do not exist nationally. Sandia maintains a core capability in hydrogen embrittlement of structural materials, in which the Hydrogen Effects on Materials Laboratory is the central asset. This laboratory features several specialized systems for measuring the mechanical properties of materials in high-pressure gaseous hydrogen; however, fatigue evaluation of materials is limited to testing at room temperature. Work is underway to add variable temperature testing to the fatigue testing capabilities in the Hydrogen Effects on Materials Laboratory.

The major components of the apparatus for variable-temperature testing in hydrogen has have been acquired. The final procurements are being made with investment from both FCTO and NNSA. The Advancing Materials Testing in Hydrogen Gas workshop hosted by Sandia in March 2013 was instrumental in focusing attention on an internal cooling mechanism for the pressure vessel. A prototype cooling mechanism was designed and tested under ambient conditions. This mechanism is relatively simple in concept, consisting primarily of a copper-cooling block in contact with a stainless steel tube carrying cryogenic fluid (Figure 2a). This prototyping activity demonstrated that the target temperature of 223K (-50^{o}C) could be attained at a cylindrical stainless steel test specimen surrounded by the copper-cooling block. In parallel with this successful prototyping, a student intern at Boise State simulated the temperature distribution in the concept pressure vessel with internal cooling mechanism. Example results from these SolidWorks simulations are displayed in Figure 2b.

Once operational, this system will provide system designers with data necessary to develop robust, cost effective low temperature hydrogen systems for storage and dispensing applications.

International collaboration with I2CNER

Significant resources are being invested around the world in hydrogen material research. The International Institute for Carbon-Neutral Energy Research (I2CNER) is one of the premier organizations dedicated to the advancement of hydrogen materials science. Through coordination of hydrogen materials science research in the US and Japan, hydrogen technology can be accelerated. Dr. Brian Somerday leads the Hydrogen Materials Compatibility (HMC) division of I2CNER, providing a direct link between hydrogen embrittlement studies across the Pacific. Dr. Somerday co-organized several high-profile events for I2CNER in FY14:

- Coordination meeting for the HMC division at Yufuin, Japan to promote interaction within the division and refine the research roadmap of the division (December 2013)
- The Joint HYDROGENIUS and I2CNER International Workshop on Hydrogen-Materials Interactions at the International Hydrogen Energy Development Forum in Fukuoka, Japan (January 31, 2014)

Leveraging partnership at AIST

International harmonization of methods for qualifying materials for hydrogen service is widely recognized as critical to the deployment of hydrogen technologies. Sandia interacts broadly with international partners to promote unified test methods, including research collaboration with staff from AIST (who visit Sandia regularly). The Sandia team hosted the SNL-AIST Workshop on High-Pressure Hydrogen Storage Systems in January 2014. The main outcomes of the workshop were: (i) plan for proposing revision of ASTM testing standards to include special requirements for testing gaseous hydrogen; (ii) identification of opportunity for risk analysis around materials and pressure vessels; and (iii) extension of materials testing activities in gaseous hydrogen. Risk analysis and future testing is contingent on budgets. Figure 3 shows the foundational data generated collectively by SNL and AIST; these data are anticipated to influence testing standards, such as those from ASTM International. Several papers were prepared jointly by SNL and AIST to be presented at the ASME 2014 Pressure Vessel and Piping Division Conference.

Conclusions and Future Directions

- Fatigue life testing on the stainless steel 21Cr-6Ni-9Mn in 103 MPa hydrogen gas has two potential impacts: quantitative evaluation of methods recently published in the CSA CHMC1 standard and qualification data for a lower-cost stainless steel.
- Progress in developing the variable-temperature testing system bolsters the core capability for materials characterization in high-pressure hydrogen and assures critical testing can be performed on technologically pivotal materials such as stainless steels.
- International partnerships with I2CNER and AIST provide access to basic science related to materials behavior in hydrogen and data that enable the development of international standards for materials testing and component qualification.
- (future) Formalize schema for material property database in Granta MI.
- (future) Commission variable-temperature testing in hydrogen gas system: integrate subsystems and demonstrate functionality.
- (future) Continue critical evaluation of test methods in CSA CHMC1, including rate effects (AIST collaboration) and “safety factor method” option.
- (future) Develop R&D program with industry partner(s) to evaluate and improve resistance of high-strength structural metals to hydrogen-assisted fracture.

Special Recognitions & Awards/Patents Issued

1. Brian Somerday and Chris San Marchi, DOE Hydrogen and Fuel Cells Program Awards, Hydrogen Delivery and Safety, Codes and Standards, 2014.

FY 2014 Publications/Presentations

1. C. San Marchi and B.P. Somerday, "Comparison of stainless steels for high-pressure hydrogen service" (PVP2014-2881), accepted for ASME 2014 Pressure Vessel and Piping Division Conference, Anaheim CA, 20-24 July 2014.
2. T. Iijima, B. An, C. San Marchi, B.P. Somerday, "Measurement of fracture properties for ferritic steel in high-pressure hydrogen gas" (PVP2014-28815), accepted for ASME 2014 Pressure Vessel and Piping Division Conference, Anaheim CA, 20-24 July 2014.
3. B. An, T. Iijima, C. San Marchi, B.P. Somerday, "Micromechanisms of hydrogen-assisted cracking in super duplex stainless steel investigated by scanning probe microscopy" (PVP2014-28181), accepted for ASME 2014 Pressure Vessel and Piping Division Conference, Anaheim CA, 20-24 July 2014.
4. (invited) J. Ronevich, B. Somerday, C. San Marchi, H. Jackson, and K. Nibur, "Fracture Resistance of Hydrogen Precharged Stainless Steel GTA Welds", SteelyHydrogen 2014: Second International Conference on Metals & Hydrogen, Ghent, Belgium, May 2014.
5. (invited) B. Somerday, "Technological and Industrial Progress in Hydrogen and Fuel Cells in the U.S.", International Hydrogen Energy Development Forum 2014, Fukuoka, Japan, Jan. 2014.
6. C. San Marchi and B.P. Somerday, "Design philosophies for high-pressure hydrogen storage systems". Presented at the AIST-SNL Workshop on High Pressure Hydrogen Storage Systems, Livermore CA, January 24, 2014 (SAND2014-0538P).
7. H.F. Jackson, C. San Marchi, D.K. Balch, B.P. Somerday, "Effect of low temperature on hydrogen-assisted crack propagation in 304L/308L austenitic stainless steel fusion welds". Corros Sci 77 (2013) 210-221.
8. C. San Marchi, B.P. Somerday, K.A. Nibur, "Development of methods for evaluating hydrogen compatibility and suitability", accepted to Intern J Hydrogen Energy.
9. L.A. Hughes, B.P. Somerday, D.K. Balch, C. San Marchi, "Hydrogen compatibility of austenitic stainless steel tubing and orbital tube welds", accepted to Intern J Hydrogen Energy.
10. R.R. Barth, K.L. Simmons, C. San Marchi, "Polymers for Hydrogen Infrastructure and Vehicle Fuel Systems: Applications, Properties and Gap Analysis" SAND2013-8904 (October 2013).
11. C. San Marchi, B.P. Somerday, K.A. Nibur, "Measuring fracture properties in gaseous hydrogen", presented at International Workshop on Hydrogen Embrittlement in Natural Gas Pipelines, Seoul, Korea, November 27, 2013 (SAND2013-10058P).
12. C. San Marchi, "Hydrogen transport in metals", invited presentation at Korean Research Institute of Standards and Science, Daejeon, Korea, November 2013 (SAND2013-10059P).
13. C. San Marchi, K.A. Nibur, "Materials qualification for hydrogen service using CSA CHMC1", presented at to Japanese stakeholders during informational meeting at SNL/CA, November 8, 2013 (SAND2013-9607P).
14. M. Dadfarnia, B.P. Somerday, P.E. Schembri, P. Sofronis, J.W. Foulk, III, K.A. Nibur, and D.K. Balch, "On Modeling Hydrogen Induced Crack Propagation Under Sustained Load", *JOM*, 2014, in press.
15. B.P. Somerday and M. Barney, "Measurement of Fatigue Crack Growth Relationships in Hydrogen Gas for Pressure Swing Adsorber Vessel Steels", *Journal of Pressure Vessel Technology*, 2014, accepted for publication.

Acronyms

AIST – Advanced Industrial Science and Technology

ASME – American Society of Mechanical Engineers
CHMC – Compressed Hydrogen Material Compatibility
FCTO – Fuel Cell Technologies Office
I2CNER – International Institute for Carbon-Neutral Energy Research
MDMC – Material Data Management Consortium
NNSA – National Nuclear Security Administration

Figures

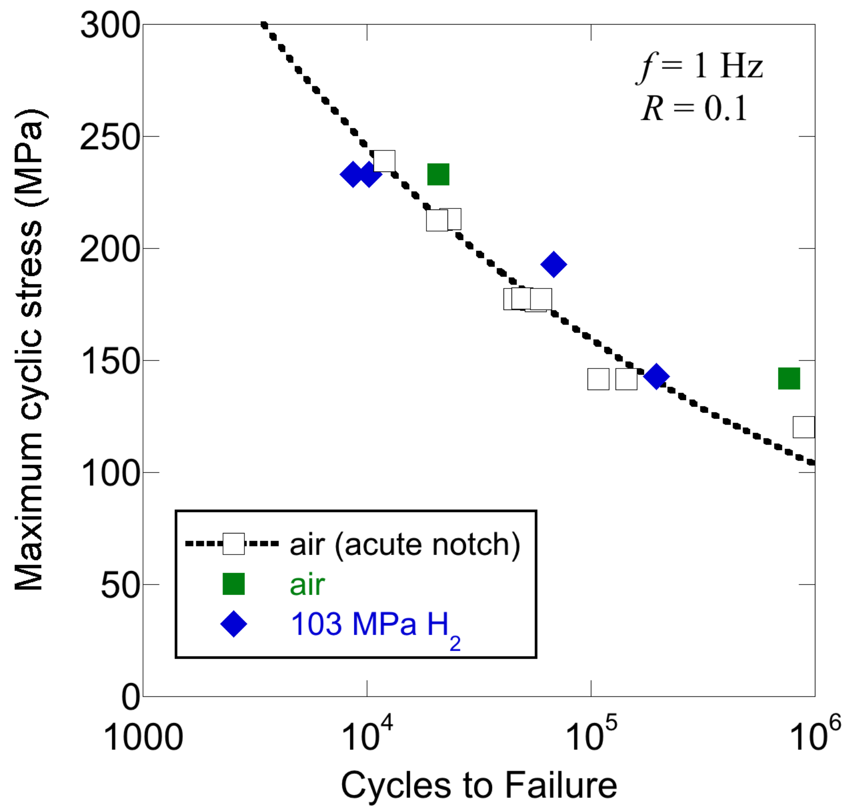

Figure 1. Stress amplitude-cycles to failure plot for notched cylindrical fatigue tests, comparing tests in gaseous hydrogen with tests in air; open symbols represent tests in air with an acute notch, while closed symbols represent specimens with a notch as called out in CSA CHMC1.

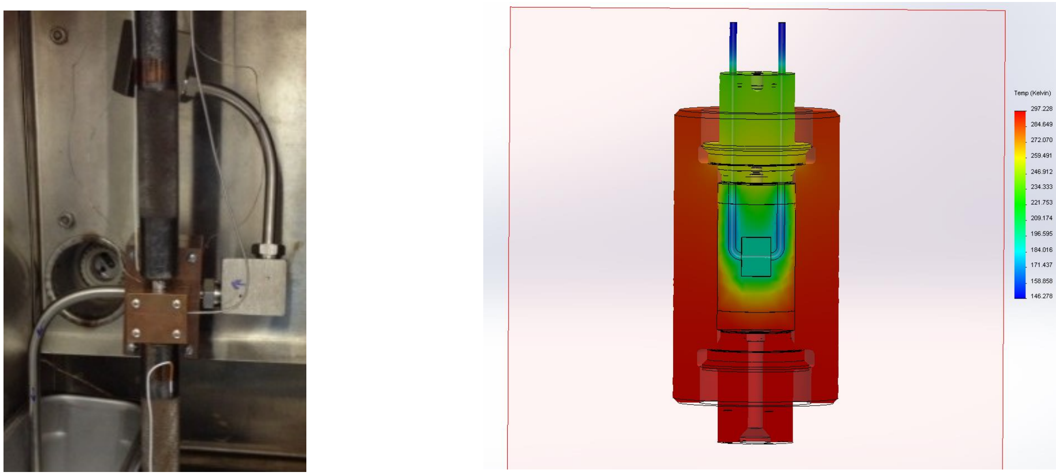

Figure 2. (a) Prototype cooling mechanism consisting of copper cooling block with stainless steel tubing carrying cryogenic fluid. (b) SolidWorks simulation of temperature distribution in pressure vessel with internal cooling mechanism.

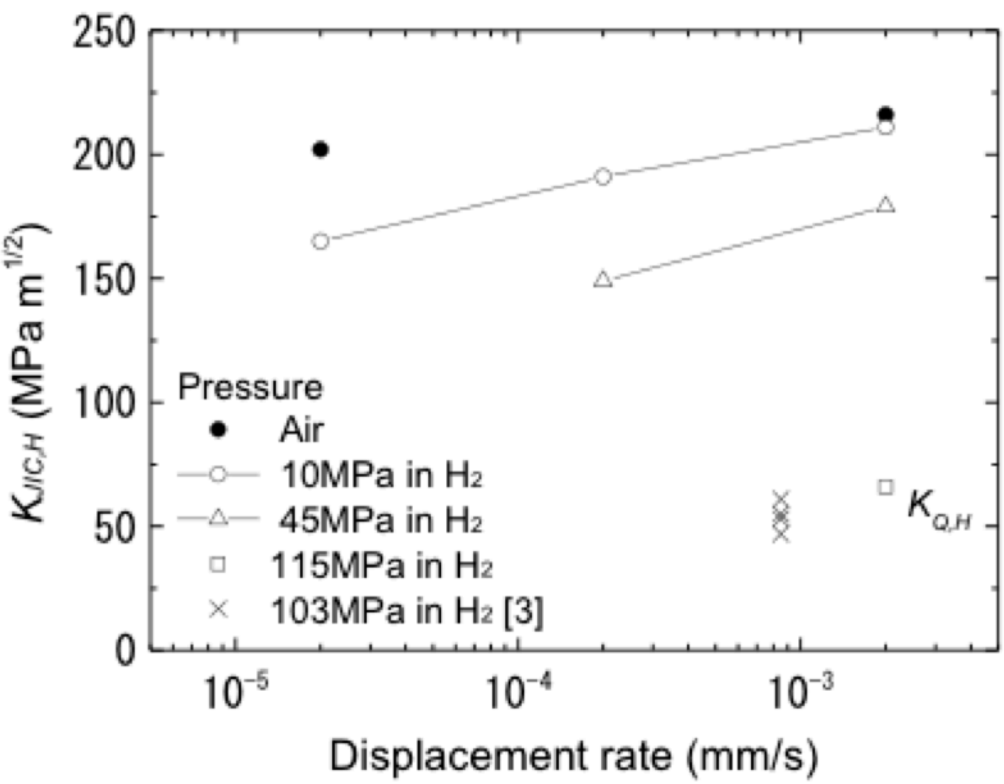

Figure 3. Rising-displacement fracture thresholds measured for SA372 Grade J pressure vessel steel in air and high-pressure hydrogen gas. Data points in plot represent measurements from both SNL (cross symbols) and AIST (other symbols).

R&D for Safety Codes and Standards: Hydrogen Release Behavior and Risk Assessment

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DOE Managers (will be supplied – no input required)

Project Start Date: October 1, 2003

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

Overall Objectives

- Build tools to enable industry-led C&S revision and safety analyses to be based on a strong science and engineering basis.
- Develop & validate H2 behavior physics models to address targeted gaps in knowledge.
- Develop H2-specific Quantitative Risk Assessment (QRA) tools and methods to support RCS decisions and to enable Performance Based Design (PBD) code-compliance option.
- Eliminate barriers to deployment of hydrogen fuel cell technologies through scientific leadership in codes and standards development efforts.

Fiscal Year (FY) 2014 Objectives

- Develop version 1 of an integrated hydrogen specific risk assessment toolkit (HyRAM) to enable sustained use of QRA by a broad range of users
- Initiate research activity with industrial partners to use QRA tool to implement and validate performance-based compliance approach of NFPA2 Chapter 5.
- Develop technical plan and partnerships for building experimental test platform for hydrogen release behavior at cryogenic temperatures.
- Conduct modeling and experimental activities to develop and validate reduced order modeling of jet flame behavior and deflagration overpressures.
- Provide expert perspective on QRA and behavior models to relevant codes and standards committees to promote the adoption of science-based methods.

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 – parking structures, tunnels and other usage areas.

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 Program Multi-Year Research, Development and Demonstration Plan:

- Milestone 2.8: Publish risk mitigation strategies. (2Q, 2014)
- Milestone 2.7: Provide critical understanding of hydrogen behavior relevant to unintended releases in enclosures. (4Q, 2013)

- Milestone 2.10: Understand flame acceleration leading to transition to detonation. (4Q, 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 2014 Accomplishments

- Report: developed a metric to evaluate the development of hydrogen codes and standards and benchmarked program activity to show progress in enabling technology deployment
- Workshop: organized and led hydrogen C&S QRA user workshop to help build stakeholder awareness of risk and to identify barriers that limit industry use of QRA
- Developed an integrated reduced-order behavior model for predicting overpressures associated with transient hydrogen releases for use in risk-informed C&S development.
- Developed a detailed project plan to research and model the behavior of unintended releases of hydrogen at cold and cryogenic temperatures
- Updated existing reduced-order flame radiation models with large scale, downstream flame radiation behavior to improve prediction of downstream heat flux

Introduction

DOE FCTO has identified safety, codes, and standards as a critical barrier to the deployment of hydrogen, with key barriers related to the availability and implementation of technical information in the development of Regulations, Codes and Standards (RCS). This project provides the technical basis for assessing the safety of hydrogen fuel cell systems and infrastructure using quantitative risk assessment (QRA) and physics-based models of hydrogen behavior. The risk and behavior tools that are developed in this project are motivated by and shared directly with 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. The behavior of hydrogen releases is examined using state-of-the-art diagnostics in the Turbulent Combustion Laboratory. Results of these experiments are used to develop and validate predictive engineering tools for flame initiation, flame sustainment, radiation patterns, and overpressures. The resulting behavior models provide the foundation for QRA modeling efforts, which include scenario analysis, consequence modeling, and quantification of risk. These integrated 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

Develop version 1 of an integrated hydrogen specific risk assessment toolkit (HyRAM)
Code committees and industry are both interested in using QRA to enable code development and code compliance for hydrogen systems. Gaps and limited availability of QRA tools for hydrogen form a barrier to this goal. This core research activity addresses the hydrogen QRA tool gap by

integrating validated models and data into a Windows-based engineering tool with a graphical user interface (GUI).

Figure 1 is a flowchart that shows the various modules used within HyRAM. Initial elements of the flowchart were independently developed in Matlab. The unified HyRAM tool replaces this array of independent modules to enable broader application of QRA by stakeholders. The modular architecture and open-source license set the stage for future development activities to occur collaboratively with other research organizations. HyRAM version 1 contains GUIs for "QRA mode," which enables end-to-end use of the HyRAM modules to calculate risk from jet flames for user-defined gaseous hydrogen systems. Toolkit priorities are based on published proceedings of the QRA user workshop held in June 2013. Version 1 of HyRAM, which is to be completed at the end of 2014, can be used to quantify the likelihood and thermal consequences associated with jet fires from gaseous releases from user-defined hydrogen installations. Future development activities include enabling stand-alone use of behavior models for consequence calculations and the addition of new consequence calculations (such as overpressure) to expand the type of infrastructure that can be modeled in HyRAM.

Cold and cryogenic hydrogen behavior research

Bulk liquid hydrogen storage has the benefit of a higher storage potential that enables greater station throughput over similarly sized gaseous systems. However, validated models of liquid hydrogen releases — critical information needed for risk-based strategies — do not exist, due to a lack of adequate data from science-based test platforms with full control over release boundary conditions. Sandia developed a detailed project plan to research and model the behavior of unintended releases of hydrogen at cold and cryogenic temperatures. Additionally, under a cooperative research and development agreement with industry, we have begun designing an experimental platform for generating the missing data. The preliminary design is shown in Figure 2. After installation and performance-testing of the cryogenic hydrogen release laboratory are complete (targeted for late 2015), the laboratory will be used to develop comprehensive data sets relevant to releases from liquid hydrogen storage systems similar to those located at commercial fueling stations. This will enable development and experimental validation of cold-plume release models that can be integrated into QRA and safety assessments to enable deployment of liquid hydrogen infrastructure.

Hydrogen behavior modeling and experimental validation

Ongoing research occurring over the past decade at Sandia years has resulted in the development and validation of numerous scientific models of the behavior of gaseous hydrogen releases. During FY14, the jet flame model was updated to account for downstream buoyancy behavior that was observed during experimental validation activities. This and other physical models (products of several years of research in this program) are being consolidated, modularized, and documented for integration into the HyRAM toolkit. Gaseous hydrogen jet dispersion models and jet flame models (along with the required sub-models, e.g., notional nozzle models) were formalized and integrated into HyRAM during FY14. Ongoing activity includes a first-order overpressure model suitable for integrating into HyRAM in the FY15 timeframe. Several of these models and their sub-models require additional validation data and further refinement, including the overpressure model, the notional nozzle model, and models of liquid hydrogen behavior. Additionally, we are planning experiments to reduce the ambiguity in the notional nozzle (under-expanded jet) model in collaboration with a student from Tsinghua University.

Develop design brief to enable performance-based compliance option

NFPA 2, Hydrogen Technologies Code, allows for the use of performance-based design (PBD) for hydrogen facilities as a means of complying with the code without strict adherence to the prescriptive code requirements. While HyRAM can be used as a means of evaluating the risk of alternate designs, it can also be used to quantitatively evaluate risks associated PBD options. The establishment and demonstration of PBD option will directly increase the availability of locations for hydrogen fueling stations, reduce the effort required by industry to use the PBD approach and lay the groundwork for similar QRA-backed design processes for other alternative fuels. In order to initiate real-world application of science-based risk analysis, a Cooperative Research and Development Agreement (CRADA) was initiated with a major hydrogen fueling station provider.

Figure 3 depicts the approach of the application of QRA to the design of both a representative commercial hydrogen refueling station and a real-world station. The HyRAM software will be used to calculate the risk metrics for a station that is fully compliant with the prescriptive code requirements in order to establish a baseline for these metrics for a specific station configuration. In the next phase of work, a station design with key modifications to the prescriptive requirements will be evaluated with input from the industry partner. This mock PBD will then be vetted with in the fire protection and hydrogen industries with the aim of identifying best practices for implementing PBD methods. Following this, a real-world station with a key modification backed by a performance-based design will be processed through the permitting process for a hydrogen station in California.

Codes and standards participation

- CSA HGV 4.9 – Hydrogen Fueling Station guidelines has been edited and reorganized and is ready for industry review before it becomes a CSA standard.
- Hydrogen Safety Panel – Sandia participated in several hydrogen safety plan reviews for innovative industrial hydrogen implementations as well as participating in the revision of the hydrogen event data collection fields.
- NFPA2 – Sandia participated in the 2nd draft meeting of the 2016 version of NFPA 2 Hydrogen Technologies Code. Sandia also actively participated in the reactivation of the NFPA 2 liquid hydrogen separation distances task group, which began work on revision of the prescriptive requirements for the next revision cycle of the code.

Conclusions and Future Directions

- Program impact is demonstrated by benchmarking metric: "Number of sites that can readily accept hydrogen"
    - (future) Re-evaluate benchmark to evaluate R&D investments at key project milestones and to ensure continued alignment with program goals.
- A template for implementing the performance-based approach in NFPA2 Chapter 5 is the next step for increasing the number of sites that can readily accept hydrogen.
    - (future) Demonstrate PBD option and work the PBD brief through a permitting process to demonstrate acceptance of a PBD approach by an AHJ.
- HyRAM provides a standardized platform for developing and integrating hydrogen QRA and consequence models into codes and standards.
    - (future) Add reduced order overpressure model and features to enable PBD
    - (future) Formalize rules for user-defined models and international harmonization of methodology
- Improved physics-based models of hydrogen behaviors (e.g., jet flame model, multi-source radiation model) improves the fidelity of risk calculations.
    - (future) Improve the accuracy of the submodels, particularly the notional nozzle model, through targeted experiments.
- An integrated, reduced-order overpressure model enables the calculation of overpressure in HyRAM and fills a key gap in modeling hydrogen deflagrations.
    - (future) Add overpressure model into HyRAM in the early FY15 timeframe.
    - (future) Validate model accuracy and make improvements as needed.
- The storage of LH2 is limited by the existing code requirements and predictive behavior models for LH2 releases
    - (future) Construct experimental platform for characterizing the unintended release of liquid-vapor mixed-phase hydrogen releases (with support from industry)

FY 2014 Publications/Presentations

1. A.C. LaFleur, K. Groth, A.B. Muna. "Application of Quantitative Risk Assessment (QRA) to Hydrogen Fueling Infrastructure for FCEVs." Presentation at the 2014 ASME 12th Fuel Cell Science, Engineering and Technology Conference, Boston, MA, July 2014.
2. K. Groth "Hydrogen behavior and Quantitative Risk Assessment." Presentation at the 2014 DOE Hydrogen Fuel Cell Technologies Program Annual Merit Review, Washington, DC. June 2014.
3. K. Groth. "Hydrogen QRA & HyRAM Toolkit Introduction" Presentation at side-meeting on Hydrogen Risk Assessment at DOE Hydrogen Fuel Cell Technologies Program Annual Merit Review, Washington, DC. June 2014.
4. A.C. LaFleur, A.B. Muna, "Hydrogen Fueling Station Performance-Based Approach." Presented at 20th Hydrogen Safety Panel (HSP) meeting, Golden, CO, May 2014
5. K.M. Groth. "Hydrogen QRA & HyRAM Toolkit Introduction" Presented at 20th Hydrogen Safety Panel (HSP) meeting, Golden, CO, May 2014.
6. A.V. Tchouvelev, K.M. Groth, P. Benard, T Jordan. "A Hazard Assessment Toolkit For Hydrogen Applications*." Proc World Hydrogen Energy Conference* (WHEC 2014), 2014
7. K.M. Groth, A.V. Tchouvelev, "A toolkit for integrated deterministic and probabilistic risk assessment for hydrogen infrastructure*." Proc Int Conf Probabilistic Safety Assessment and Management (PSAM 12)*, June 2014.
8. I.W. Ekoto, A.J. Ruggles, L.W. Creitz, J.X. Li. "Updated Jet Flame Radiation Modeling with Corrections for Buoyancy". *Int. J. of Hydrogen Energy*, Accepted in 2014.
9. A.J. Ruggles, I.W. Ekoto. "Experimental investigation of nozzle aspect ratio effects on underexpanded hydrogen jet release characteristics*," International Journal of Hydrogen Energy*, Accepted March 2014.
10. K.M. Groth, J.L. LaChance, A.P. Harris. "Design-stage QRA for indoor vehicular hydrogen fueling systems". *Proc of the European Society for Reliability Annual Meeting (ESREL 2013).*
11. A.P. Harris, D.E. Dedrick, A.C. LaFleur and C. San Marchi, "Safety, Codes and Standards for Hydrogen Installations: Hydrogen Fueling System Footprint Metric Development." SAND2014-3416, Sandia National Laboratories, April 2014.
12. A.C. LaFleur, "Risk and Reliability Analysis" presented at AIST-SNL workshop on High Pressure Hydrogen Storage Systems, January 24, 2014.
13. K.M. Groth, "Sandia H2 Quantitative risk assessment (QRA) activities." Presented to DOE H2 CSTT, December 19, 2013.
14. A. Harris. "Survey of Materials Selection Information for Hydrogen Service" Presented to US DOE Hydrogen Safety Panel meeting, December 11, 2013.
15. A. Harris. "Leak Rate Standard Working document" Presented to US DOE Hydrogen Safety Panel meeting, December 11, 2013.
16. A. Harris. "Results from a case study of separation distances in support of program performance metric development for US DOE EERE FCTO" Presented to California Fuel Cell Partnership, December 4, 2013.
17. K.M. Groth, "SNL QRA toolkit and SNL-HySafe workshop." Presented to International Energy Agency Hydrogen Implementing Agreement Task 31 experts workshop (IEA HIA), October 15, 2013.
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Acronyms

C&S	Codes and standards
CRADA	Cooperative Research and Development
FY	Fiscal Year
GUI	Graphical User Interface
HyRAM	Hydrogen Risk Assessment Models
NFPA	National Fire Protection Association
QRA	Quantitative Risk Assessment
PBD	Performance-Based Design
RCS	Regulations, Codes and Standards
SNL	Sandia National Laboratories

Figures

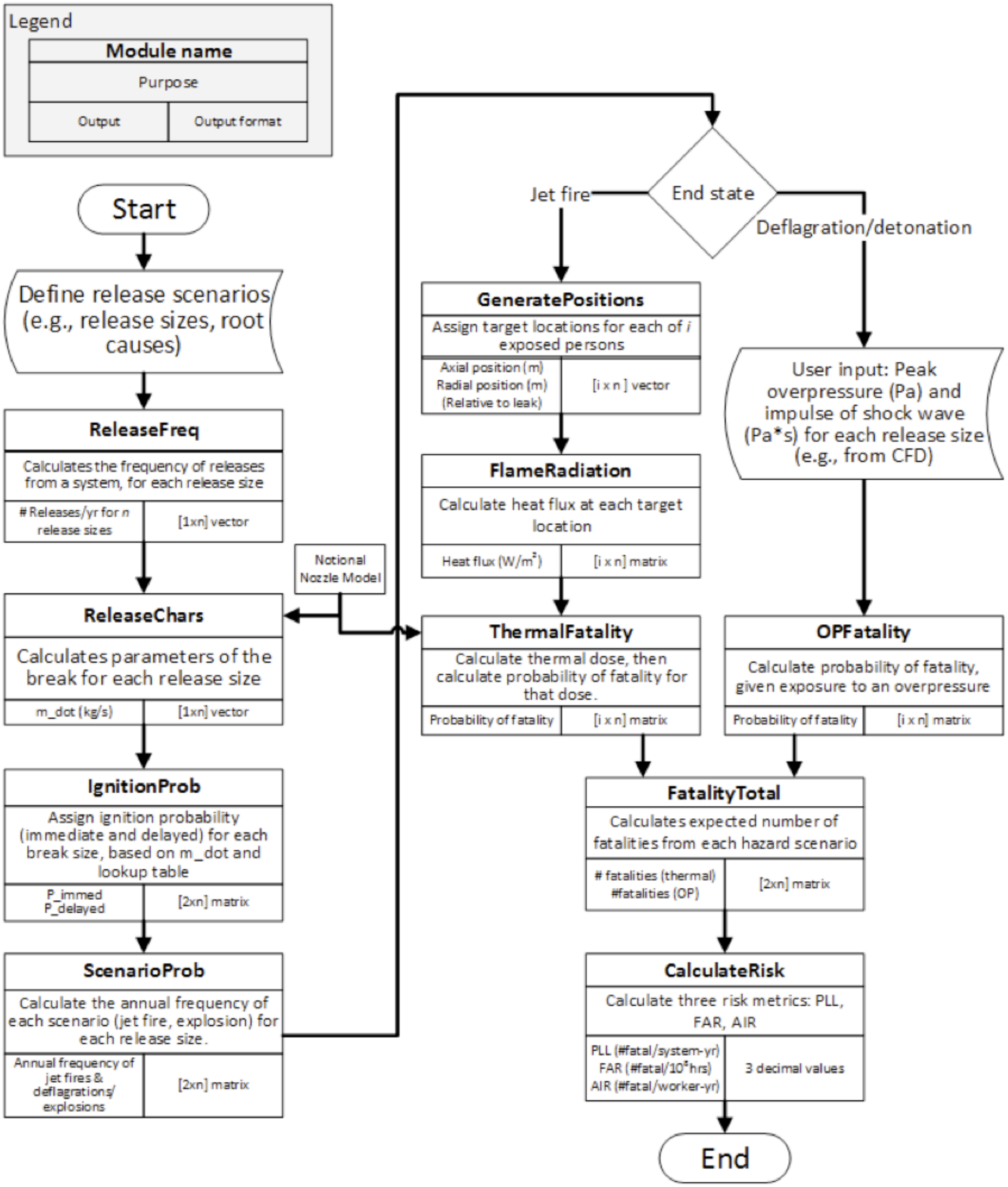

Figure 1. Flowchart of modules contained in the HyRAM toolkit. Modules can be used end-to-end, as illustrated in this figure, or in stand-alone calculations.

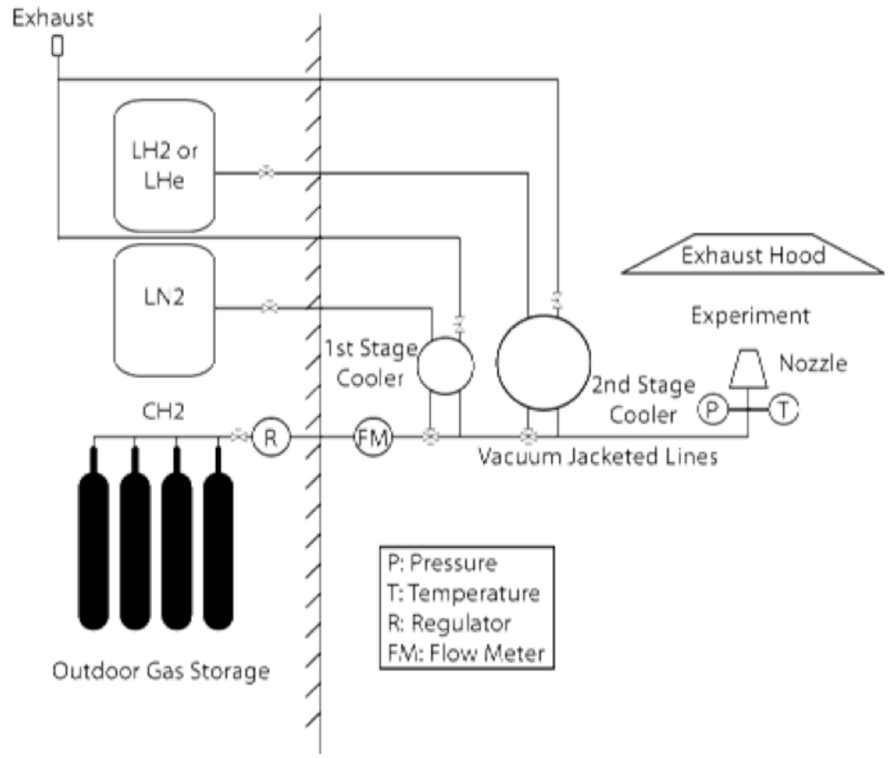

Figure 2. Cryogenic release laboratory design. Gaseous hydrogen is cooled in two stages, by liquid nitrogen and then liquid hydrogen, before release.

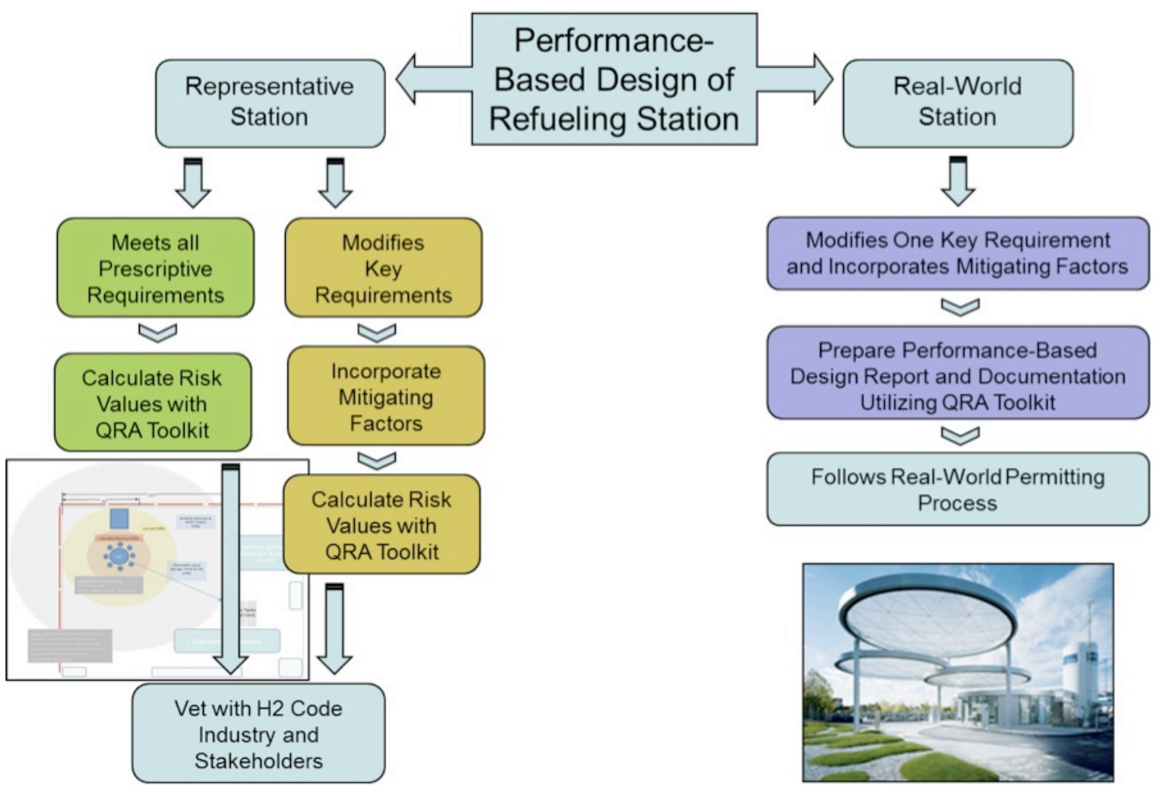

Figure 3. Overview of Performance-Based Design Application of QRA