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Hydrogen Quantitative Risk Assessment Workshop Proceedings

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Abstract

The Quantitative Risk Assessment (QRA) Toolkit Introduction Workshop was held at Energetics on June 11-12. The workshop was co-hosted by Sandia National Laboratories (Sandia) and HySafe, the International Association for Hydrogen Safety. The objective of the workshop was twofold: (1) Present a hydrogen-specific methodology and toolkit (currently under development) for conducting QRA to support the development of codes and standards and safety assessments of hydrogen-fueled vehicles and fueling stations, and (2) Obtain feedback on the needs of early-stage users (hydrogen as well as potential leveraging for Compressed Natural Gas [CNG], and Liquefied Natural Gas [LNG]) and set priorities for "Version 1" of the toolkit in the context of the commercial evolution of hydrogen fuel cell electric vehicles (FCEV). The workshop consisted of an introduction and three technical sessions: Risk Informed Development and Approach; CNG/LNG Applications; and Introduction of a Hydrogen Specific QRA Toolkit.

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NOMENCLATURE

DOE	Department of Energy
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1. INTRODUCTION

The Quantitative Risk Assessment (QRA) Toolkit Introduction Workshop was held at Energetics on June 11-12. The workshop was co-hosted by Sandia National Laboratories (Sandia) and HySafe, the International Association for Hydrogen Safety. The objective of the workshop was twofold: (1) Present a hydrogen-specific methodology and toolkit (currently under development) for conducting QRA to support the development of codes and standards and safety assessments of hydrogen-fueled vehicles and fueling stations, and (2) Obtain feedback on the needs of early-stage users (hydrogen as well as potential leveraging for Compressed Natural Gas [CNG], and Liquefied Natural Gas [LNG]) and set priorities for "Version 1" of the toolkit in the context of the commercial evolution of hydrogen fuel cell electric vehicles (FCEV). The workshop consisted of an introduction and three technical sessions: Risk Informed Development and Approach; CNG/LNG Applications; and Introduction of a Hydrogen Specific QRA Toolkit.

Risk Informed Approach Development and Application

Session 1 provided insight into how QRA has been and will be used in the hydrogen fuel cell industry (and similar industries). The term "QRA" encompasses a variety of tools, models, and techniques, and can be used to meet a variety of analysis goals. During this session, presenters documented QRA approaches and example applications for compressed gaseous fueled transportation applications. This session included a presentation by Professor Mohammad Modarres who was invited to present a case study documenting a comprehensive QRA on CNG-fueled buses. An industry panel provided feedback on industry needs and questions with regards to the use of QRA. The session concluded with a guided discussion on QRA needs for the hydrogen fuel cell industry and for hydrogen codes & standards.

QRA for CNG and LNG

Session 2 explored how natural gas (in liquid and compressed form) is being considered as a transportation fuelfor both automotive and railroad applications. The safety impacts and mitigation strategies for compressed natural gas are similar enough to hydrogen that an opportunity exists to leverage the tools and methods under development for hydrogen. This session explored that opportunity and set the stage for follow-up discussions with CNG and LNG stakeholders in the toolkit development. This session consisted of hydrogen focused participants as well as additional stakeholders from the CNG and LNG community.

Tools for Risk Informed Analysis

Session 3 introduced participants to the first version of a hydrogen QRA toolkit and obtained feedback and suggestions for transitioning the toolkit to enable the use of QRA more broadly within the hydrogen fuel cell industry. The presentations in this section described the motivation for creating a QRA toolkit and described the first version (Version 0) of the toolkit. These presentations set the stage for the break out groups and discussion in the afternoon. The breakout discussions focused on establishing user needs and prioritizing improvements to the toolkit.

Conclusions

The workshop conclusions included the recommendations to the toolkit development team. The participants recommended that the team identify two audiences or user groups: one group, called "USERS," are non-experts who will use the toolkit for codes and standards development, system design and other technology deployment activities. The second group, "DEVELOPERS," is the existing international research community who are concerned with consequences such as deflagrations, QRA methodology and other research, development, and demonstration (RD&D) topics. These communities are distinctly different and should be incorporated appropriately to enhance the toolkit development. The conclusions section provides a detailed list of recommended actions.

The project team plans to incorporate much of the advice from this workshop into the development of Version 1 of the toolkit. The goal for Version 1 is a fully integrated toolkit. The project team recognizes, and the workshop validated, the need for substantial interaction with stakeholders.

This workshop is the first of many efforts to interact with the toolkit stakeholders while the team prepares Version 1 of the toolkit. Additional formal workshops as well as invited presentations are under consideration. These additional interactions with target stakeholders (e.g., users such as the Hydrogen Technologies Code of the National Fire Pretection Agency[NFPA 2] committee, hydrogen station or system developers and the researchers associated with organizations such as HySafe).

Key takeaways from the workshop discussions include:

- Current QRA tools lack validated models and data for hydrogen fuel cell analyses.
- There is a critical need for tools that help enable two types of analysis: high level generic insights for Codes and Standards (C&S) developers, regulators, etc.; and a detailed tool for site-specific QRA for system designers, authorities having jurisdiction (AHJs), etc.
- There are relevant parallels between the CNG/LNG and hydrogen (H2) industries.
- Both CNG/LNG and H2 industries can benefit from the collection of incident data.
- There are two distinct user groups for the proposed toolkit: USERS and DEVELOPERS.
- C&S users prefer tools that facilitate relative risk comparisons.
- Developers must work with code development committees closely to identify opportunities to use the toolkit.
- Datasets must be developed specifically for use in the toolkit

1.1. Workshop Objectives and Organization

The Quantitative Risk Assessment Toolkit Introduction Workshop was held at Energetics on June 11-12. The workshop was co-hosted by Sandia National Laboratories and HySafe, the International Association for Hydrogen Safety. The objective of the workshop was twofold: (1) Present a methodology and toolkit (currently under development) for conducting QRA to support the development of codes and standards and safety assessments of hydrogen-fueled vehicles and fueling stations, and (2) obtain feedback on the needs of early-stage users (hydrogen, CNG, and LNG) and set priorities for “Version 1” of the toolkit in the context of the commercial evolution of hydrogen fuel cell electric vehicles (FCEV).

FCEV regulations, codes, and standards are in a time of transition as the industry moves from early market activities toward commercialization. The ability to rapidly quantify risk for multiple design choices will result in market acceleration.

The workshop also represents a key transition in the use of Risk Informed Decision Making (RIDM) process for hydrogen safety, codes and standards. Since 2005, quantitative analysis to support RIDM for codes and standards has been conducted by government experts. The creation of a QRA toolkit aims to transition QRA responsibility to other experts in the broader hydrogen community for use in codes and standards development and implementation during project permitting, and during product design and strategic business planning.

The workshop consisted of an introduction and three technical sessions: Risk Informed Development and Approach; CNG/LNG Applications; and Introduction of a Hydrogen Specific QRA Toolkit.

Workshop Introductions

Aaron Harris, Project Lead, Hydrogen Safety, Codes and Standards, Sandia National Laboratories. Mr. Harris provided the group with an introduction, including the workshop logistics, agenda summary and explanation of workshop objectives. Mr. Harris stressed the importance of continued interaction with the stakeholders, including an invitation to participate as a stakeholder working group and toolkit “beta tester.”

Sunita Satyapal, Director, Department of Energy (DOE) Fuel Cell Technologies Office: Dr. Satyapal provided an introduction to a new DOE initiative, the H2USA Partnership. H2USA is a public-private partnership to promote the commercial introduction and widespread adoption of hydrogen fuel cell technologies. This is the first initiative where major US companies and state and federal agencies are working together to address hydrogen infrastructure. The hydrogen fuel cell industry is rapidly expanding in the United States, and many stakeholders are working with DOE to enable continued growth.

Erika Sutherland, Technology Development Manager, Delivery Subprogram, Department of Energy Fuel Cell Technologies Office: Ms. Sutherland provided an overview of the mission of the Hydrogen and Fuel Cells Program and the Safety, Codes and Standards (SCS) team. The main goal of the program is to facilitate widespread adoption of fuel cell technologies. Fuel cells are an important part of the DOE’s portfolio because of their flexibility, scalability, and broad applicability; they have applications in transportation, stationary power, and portable and grid energy storage.

Safety, codes, and standards play a critical role in technology deployment. A key goal of the SCS team is to ensure that stakeholders have the right information to make safety critical decisions, including the development of regulations, codes, and standards. To this end, the SCS subprogram is sponsoring several projects, including QRA work and a voluntary incident reporting database: www.h2incidents.org. QRA is an important tool that can be used to help establish safe hydrogen systems. A critically important part of the RIDM process is to understand the needs of the regulations, codes, and standards developers. What consequences are important? How much information is needed to make decisions? What specific questions are they trying to answer that have not been identified?

Andrei Tchouvelev, **President, HySafe**: Dr. Tchouvelev stated that the development of simplified tools for hazard assessment has been on the agenda of the international hydrogen safety community for many years. This workshop is an important opportunity to catalyze international work in hydrogen safety and to expand collaboration, particularly within the International Energy Agency (IEA) Hydrogen Implementing Agreement, and transfer knowledge to the larger community. We hope to promote the development of a tool that will enable users in the hydrogen fuel cell industry to perform QRA rooted in the best available data, validated and/or standardized models, and industry best practices. We anticipate that such a tool would be valuable for a range of stakeholders, including design and process engineers from the industry, standard development experts, risk analysts and QRA professionals, and technical authorities.

2. SESSION 1 –QRA APPROACHES AND APPLICATIONS RELATED TO HYDROGEN FUEL CELLS.

This session reviewed the history of RIDM process in applications where hydrogen is used as a vehicle fuel.

The purpose of this session was to gain insight into how QRA has been and will be used in the hydrogen fuel cell industry (and similar industries). The term "QRA" encompasses a variety of tools, models, and techniques, and QRA can be used to meet a variety of analysis goals. During this session, presenters documented QRA approaches and example applications for compressed gaseous fueled transportation applications. This session included a presentation by Professor Mohammad Modarres who was invited to present a case study documenting a comprehensive QRA on CNG-fueled buses. An industry panel provided feedback on industry needs and questions with regards to the use of QRA. The session concluded with a guided discussion on QRA needs for the hydrogen fuel cell industry and for hydrogen codes & standards.

Presentations

Andrei Tchouvelev (AVT / HySafe) **and Jeffrey LaChance** (Sandia): Dr. Tchouvelev provided a summary of the use of QRA within the hydrogen industry. RIDM processes were first used in the 1990s in the nuclear power industry; they were first referenced for hydrogen SCS in a 2005 paper for the International Conference on Hydrogen Safety. Prior to this work, the industrial gas community often used consequence-based approaches instead of risk-informed approaches. Since that time, the risk informed approach has greatly changed the landscape of the suite of codes and standards used for siting and permitting hydrogen fuel installations.
Dr. Tchouvelev discussed both qualitative risk assessment and quantitative risk assessment techniques that can be used to inform codes and standards. He emphasized the importance of using an evidence-based process, which entails using a combination of scientific information, best practices, data, and validated models to provide input for risk assessment. He also emphasized the use of a risk-informed process (as opposed to a risk-based process) where risk assessment results become an important part, but not the only part, of the decision making process.

The main focus of Dr. Tchouvelev's presentation was the development of a QRA process for hydrogen systems, which can be used as part of a process to establish minimum codes and standards' requirements for hydrogen applications. The method discussed in this presentation steps from IEA Hydrogen Implementing Agreement Task 19/Task 31 activities conducted by the presenters. Key hazards associated with hydrogen are related to the release of hydrogen, and accidents that lead to hydrogen reactions inside of a system. Dr. Tchouvelev's suggested approach includes the use of: standardized risk terminology from ISO/IEC Guide 51 (*Safety aspects – Guidelines for their inclusion in standards*) and ISO/IEC Guide 73 (*Risk management – Vocabulary – Guidelines for use in standards*), Event Tree and Fault Tree analysis, consequence models (including explosion overpressures, radiative and convective heat flux, cryogenic effects, and asphyxiation), harm models (either single criteria or probit models for various hazards), and risk acceptance criteria (either as low as reasonably practical (ALARP) or comparison to international risk acceptance criteria). He indicated the importance of using appropriate data (for frequency/probability of events, component failures, human errors, etc.) and including human errors in the analysis, but did not suggest specific models. In this analysis, human injury or fatality is the risk measure; Dr. Tchouvelev acknowledged that economic losses and environmental damage may also be of interest to some parties.

Dr. Tchouvelev identified several key needs for hydrogen QRA. These needs include: methods and data for modeling human errors, a framework for addressing uncertainty in RIDM, capability to address external hazards, and development of processes to ensure QRA quality.

Jeffrey LaChance (Sandia): Mr. LaChance presented a series of applications of the QRA process discussed in the first presentation to risk-inform codes and standards.

The QRA process was used in combination with stakeholder interaction to determine separation distances for use in NFPA and ISO hydrogen codes and standards. Prior to the use of QRA, separation distances were established using expert judgment. The QRA analysis addressed random leakage events and thermal consequences. In this analysis, Mr. LaChance used first-order models for heat flux consequences, and leak frequency data established through Bayesian analysis, and ignition probabilities developed by Andrei Tchouvelev for hydrogen based on Cox & Lees data for natural gas. A maximum risk guideline of 2E-5 fatalities/year was established based on comparison to fatality incidents at gasoline stations. Separation distances were established based on a “no harm” criteria (maximum heat flux) applied to the largest expected leak size (the leak size corresponding to the 95^{th} percentile of the leak frequency distribution established by Mr. LaChance). QRA was used to determine that larger leaks would not exceed the risk guideline.

Mr. LaChance also discussed quanitfying the risk reduction potential of accident mitigation features such as leak detectors, barrier walls, and flow orifices. To accomplish this work, he conducted sensitivity analysis on the QRA model developed for the separation distance work. This work demonstrated that the use of flow-limiting orifices and/or barrier walls can decrease the consequences of a hydrogen release. The work also found that the frequency of leaks increases as number of components in a system increases.

Mr. LaChance identified the following key needs for hydrogen QRA: data to procedure hydrogen-specific component failure frequencies, data on human errors and initiators, a more robust ignition probability model, ignition data, and first-order consequence models for determining consequences of ignited hydrogen.

Invited speaker, **Mohammad Modarres** (University of Maryland, Reliability Engineering Department):

Professor Modarres provided an overview of how risk assessment methods can be used to achieve a wide range of industrial and regulatory goals, throughout the design, operation, and maintenance of a facility. He provided a comprehensive overview of the engineering risk assessment process, including definitions of risk and various types of losses and consequences

that can be addressed in the risk assessment process (qualitative or quantitative). He provided a comprehensive list of hazards, barriers and causes and consequences of hazard exposure.
The main focus of Dr. Modarres' presentation was a case study conducting QRA as a tool to investigate fire safety aspects associated with the use of CNG-fueled buses. The goal of this work was to identify risk-significant fire scenarios, to assess fire-caused fatality risk, and to compare CNG bus fire risks to risk from diesel buses. The primary hazards addressed in this analysis are natural gas fire and explosion.

Dr. Modarres used an Failure Mode and Effects Analysis (FMEA) and review of accident scenarios to identify scenarios and barriers for the QRA. The analysis included events related to operation, maintenance, and fueling of the vehicles.

In conducting the QRA, Dr. Modarres used Event Tree and Fault Tree analysis, physics-of-failure models to assess frequency of tank failures, and failure data from industry (this data cannot be released). Releases were the result of both random failures, of gradual andcontinuous degradation of system components, and of "planned" releases. Subsequent ignition often occurred due to sparks from mechanical components (e.g., brakes), electrostatic discharge, or spreading of fire from non-CNG sources. Dr. Modarres found it necessary to address both the release characteristics and characteristics of the exposed population to address the risk, since any release could result in many different fire scenarios, and each fire scenario could result in a range of consequences depending on the population exposed to the fire.

Risk was presented as expected number of fatalities per bus-year and per 100 million miles traveled. These risk values were compared to historical data on fatalities among diesel school bus occupants. Dr. Modarres used sensitivity and importance analysis to identify the components that are the greatest contributors to the fire fatality risk.

Professor Modarres identified the following key needs for hydrogen QRA: inclusion of uncertainty analysis in QRA output, use of both historical data and operating experience (to root the analysis in evidence) plus physical analyses (to account for differences that can result in failures, but which may not be represented in historical data), inclusion of system interactions and human-system interactions. He also emphasized the importance of being systematic and thorough when conducting QRA to ensure a comprehensive analysis of the system.

Chris LaFleur (Sandia): Dr. LaFleur provided an overview of fire risk analysis work that she conducted for General Motors (GM) prior to joining Sandia. In her work at GM, Dr. LaFleur developed an enterprise fire risk database, a framework for assessing fire frequency and severity, and tools to visually analyze and compare fire risk across the range of manufacturing processes and plants. Due to the proprietary nature of the data, the numerical results presented by Dr. LaFleur were disguised, but results were illustrative of the approaches she developed.

Dr. LaFleur used Event Tree analysis and estimated expected value of consequences based on manufacturing forecast data and industry convention. She used data on small process fire frequencies and used facility-characteristics, such as the presence of fire mitigating features, to characterize the probability of a small fire becoming a severe fire. Risk was presented in terms of Fire Risk Index (FRI, a measure of the relative potential for severe fires), and Business

Interruption Value (BIV, the potential dollar value of lost production due to fire). She implemented a comparative risk approach among all of the facilities in the analysis. Dr. LaFleur noted that in industry, the notion of "acceptable risk" is not accepted; no probability of loss is acceptable to industry, rather, industry values guidance on how to continuously reduce risk.
Dr. LaFleur emphasized the importance of communicating risk in the appropriate level of detail for the audience. Dr. LaFleur provided results in a variety of graphical formats intended to inform different decision makers at GM. Results were used to prioritize fire protection spending, to develop corporate fire protection criteria for facilities in markets with minimal legal fire code requirements, and to provide cost benefit analysis for risk reduction strategies.

User Panel

The user panel discussion focused on the status of risk assessment from the perspective representatives from different aspects of the hydrogen industry. The panel consisted of representatives from hydrogen safety (**Bill Fort**, Chair, DOE Safety Panel), hydrogen station design (**Pete Steiner**, Air Products) and underwriting (**Kumar Bhimavarapu**, FM Global). The panel was moderated by **Aaron Harris** (Sandia).

Each of the users was familiar with concepts and methods for risk analysis. According to a panelist, risk analysis is increasingly popular in industry. However, QRA is relatively expensive and there is concern that it can become overly theoretical if there is not a specific analysis focus. Industry users are aware that QRA is a predictive tool and that the analyses have limitations, however they still see value in the process. The output of analyses must be presented in the appropriate level of detail and with appropriate language for each audience.

The panelists emphasized the need for data from operating experience in the hydrogen industry in addition to experience and data from similar industries. Furthermore, the pedigree of the data was an important concern, and they urged better documentation of the underpinnings of the datasets used in risk analysis. Panelists discussed industry need for a centralized repository data, which can be made available to the entire hydrogen fuel cell community, although they acknowledged that this may be difficult to create due to the sensitivity of this type of information.

The use of data improves the QRA process, but it is also important to have a knowledgeable team of industry personnel and risk analysts to avoid "garbage in, garbage out." Key concerns are model completeness and validity of underlying assumptions. It is important to consider a broad range of consequences and to include appropriate models that cover the range of expected physical behaviors of the gas and fire. The underlying assumptions in the analysis must be vetted with experienced industry personnel and with experienced risk analysts, to ensure that both industry experiences as well as best practices in QRA are contained in the analysis. Both inputs and outputs should be discussed among the experts. It is important to maintain the notion of "a room full of experts" in addition to databases to ensure that analyses are comprehensive and based on the best information, science, data, and experience.

Guided Discussion

The purpose of this discussion was to define expectations for QRA tools, methods, and data for use in applications related to hydrogen as a transportation fuel (including infrastructure development). While QRA methodology is satisfactory, no commercial tool has been developed to enable users in the hydrogen fuel cell community to leverage PRA.

Participants were asked to consider the following questions:

1) *What questions would you like QRA to answer?*
2) *What problems would you like QRA to solve?*
3) *Are available tools satisfactory for use in the hydrogen industry?*
4) *Is a QRA toolkit necessary for the hydrogen industry in 2-3 years?*

The discussion centered on identifying limitations of existing QRA tools, and defining the audience and scope for new tools to enable the use of QRA in hydrogen fuel cell applications. All attendees were involved in the discussion. Results of the discussion are included in the next section.

Key Takeaways: QRA in Hydrogen Fuel Cell Applications

***Key takeaway*: Current QRA tools lack validated models and data for hydrogen fuel cell analyses.**

Hydrogen properties, assumptions, and models are not contained in many commercial tools. Tools also lack data on releases of hydrogen from fuel cell systems. Most data is collected for large installations (e.g., offshore oil, nuclear power) and may be difficult to relate to smaller-scale hydrogen installations. Some QRA tools (e.g., SAFETI) are missing gas dispersion and overpressure models. No existing tool contains models for buoyancy-dominated hydrogen releases. Assuming a jet fire and ignoring other fire types is not conservative. It is essential to include models of actual behavior, including accumulation and ignition, and then deflagration or detonation. QRA also tends to oversimplify the way that time is considered in the analysis: for leaks and subsequent ignition, assumptions the duration and timing of both activities may significantly change the analysis. The inclusion of these elements may require a shift to simulation-based methodologies for QRA.

Furthermore, many of the models, data, and assumptions used in QRA have not been validated for application to hydrogen fuel cell infrastructure questions. The models used on the risk assessment process must be validated in the laboratory or against data as much as possible. The consequence models must have laboratory validation. Leak and ignition probability information needs to be anchored in historical data. For models that cannot be validated in the laboratory (e.g., probit models), it may be desirable to use the same models that are used in other industries to allow consistent comparison of risk. This promotes consistency in comparing H2 risk to other areas such as hydrocarbon risk. In hydrocarbon QRA, the Eisenberg probit is often used (it is implemented in PHAST, SAFETI).

***Key takeaway*: There is a critical need for tools that help enable two types of analysis: high level generic insights for C&S developers, regulators, etc., and a detailed tool for site-specific QRA for system designers, AHJs, etc.**
QRA tools are not designed to directly provide insights for codes and standards developers, system designers, or AHJs. There has been a cultural shift in industry; they are getting more comfortable with using risk information early in the design stages. However, there are very few tools available to facilitate the use of risk information during the design process. There are no tools specifically designed to help code developers, AHJs, and professional engineers develop and evaluate compliance with performance-based standards. This audience is broader than the traditional QRA audience, so education is also a key "tool."

There is a need for tools that can provide high-level insights for codes and standards developers. C&S developers need high-level insight, and could even benefit from semi-quantitative risk approaches. Furthermore, there is a need for tools that can enable exploring multiple ways to meet performance-based standards specified in NFPA 2. There is also a need for tools that help facilities perform QRA during design and installation since so many things vary from facility to facility (e.g., system design, safety equipment, barriers and mitigating features, use profile, etc.). Tools need to be able to be used by design engineers, not just code officials.

It is less urgent to provide better tools for insurers, although improvements in data will benefit all communities. Insurers often maintain their own proprietary tools, including consequence models, statistical data, etc. While these tools are not publically available, they are relatively robust when compared to the other use areas. It is unlikely that facilities would use QRA during daily operations or maintenance, so tools for these areas are unnecessary.

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3. SESSION 2 – OPPORTUNITIES FOR RISK-INFORMED ANALYSIS IN CNG AND LNG APPLICATIONS

Natural gas (in liquid and compressed form) is being considered as a transportation fuel, both for automotive and for railroad applications. The safety impacts of other compressed gas fuels are not unlike hydrogen. Tools and methods developed for hydrogen may prove very useful for CNG and LNG. In addition to the broader application of the tools, the opportunity to cost-share the tool development and expand the user/developer communities is a great opportunity. This session explored that opportunity and set the stage for follow-up discussions with CNG and LNG stakeholders in the toolkit development. This session consisted of an user panel with stakeholders from the CNG and LNG community.

User Panel

The user panel discussion focused on the needs of CNG/LNG as well as the status of tools, data, and models relevant to performing QRA for NG transportation applications. The panel consisted of representatives from regulatory agencies (**Melissa Shurland**, Federal Railroad Administration [FRA], and **Phani Raj** US Department of Transportation [US DOT]) and from CNG vehicle industry (**Doug Horne**, Clean Vehicle Education Foundation (CVEF)). The panel was moderated by **Aaron Harris** (Sandia).

The railroad industry is beginning to invest in CNG and LNG locomotives, and the industry is pushing to overturn prohibitions on transporting LNG. There is very little regulatory framework in this area because rail transportation of LNG has been restricted since the 1940s. The FRA would like to understand the risks associated with these shifts to enable appropriate regulatory development. The FRA has not previously applied risk-informed approaches, so they also need to develop a "yard stick" for measuring and characterizing risk. They are interested in the use of frequency-consequence curves (e.g., so-called "f-N curves") to demonstrate risk acceptability. The FRA is also keenly aware of the need to present risk information in an appropriate way for multiple audiences: they must engage with the railroad industry, the QRA community, and the general public.

The FRA is looking for insight into both the hazard associated with the use of CNG/LNG as a fuel, and into the probability and consequences of CNG/LNG events. They are interested in characterizing both the frequency of events and also the causal roots. FRA is also concerned with the role of humans as part of the system, including during maintenance and operations. According to Dr. Raj, 1-D behavior and consequence models may be appropriate for use within the QRA process for NG, although large scale experimentation also provides valuable insight. However, Dr. Raj emphasized the importance of modeling the fire and the system together, because separating the two parts makes it difficult to determine root causes that lead to significant consequences.

Doug Horne has been involved in NFPA and ICC code use and development since the 1990s. He strongly emphasized the need to collect data and to implement this data in the code development process. Furthermore, data collection and implementation need to be seen as an iterative process since the industry continuously evolves along with the C&S. Many codes originally implemented are prescriptive requirements designed around the consequences of a single accident such as failure of a PRD valve on a cylinder. Subsequently, PRDs have been redesigned and this failure mode has almost disappeared.

Mr. Horne has been involved in collecting data on CNG vehicle failures and accidents, and to a lesser extent on LNG vehicle incidents. Mr. Horne leveraged in the C&S process by providing insight into the root causes of failure. Mr. Horne encourages the collection of similar data for the hydrogen industry.

Key Takeaways: Opportunities for Crossover Between H2 and CNG/LNG QRA

***Key takeaway*: There are relevant parallels between the LNG/CNG and H2 industries.**

Both industries appear to be evolving at a similar pace. There is significant potential for cross-pollination in the area of data collection and human performance modeling.

***Key takeaway*: Both LNG/CNG and H2 industries can benefit from the collection of incident data.**

Similar tools can be used by both industries to enable data collection. High-level data about accidents and hazards can likely be shared between the industries. Detailed, site-specific data should be collected for both industries. Using the same framework for data collection will streamline the process and conserve resources.

4. SESSION 3 – QRA TOOLS FOR HYDROGEN FUEL CELL INDUSTRY ANALYSES

During Session 1, the workshop participants articulated a need for tools to conduct QRA for developing hydrogen C&S and for supporting safety assessments for hydrogen systems and installations.

The purpose of Session 3 was to introduce participants to the first version of a hydrogen QRA toolkit (developed for internal Sandia use) and to obtain feedback and suggestions for transitioning the toolkit to enable the use of QRA more broadly within the hydrogen fuel cell industry. The presentations in this section described the motivation for creating a QRA toolkit and described the first version (Version 0) of the toolkit. These presentations were intended to set the stage for the break out groups and discussion in the afternoon.

Presentations

Katrina Groth (Sandia) and **Jeffrey LaChance** (Sandia): The first presentation of the session was a continuation of Mr. LaChance's presentation during Session 1; this presentation set the stage for the subsequent presentation. Dr. Groth and Mr. LaChance provided a brief overview of work using QRA to establish a baseline risk for indoor fueling of hydrogen fuel cell forklifts. The work was conducted to inform NPFA 2 *Hydrogen Technologies Code*, Chapter 10 (Indoor fueling). The analysis was performed on a generic NFPA 2-compliant dispenser and warehouse design. The QRA approach was based on the approach used in the separation distance work (discussed in Session 1 by Mr. LaChance), with several extensions: the risk acceptance guideline was modified (in the forklift work, acceptance was based on comparison of Fatal Accident Rate (FAR) to accident statistics for warehouse workers); overpressure consequence models were added to the analysis; and human failure events were included in the analysis.

Katrina Groth (Sandia): Dr. Groth provided an overview of "version 0" of the hydrogen QRA tool being developed by Sandia. Version 0 was created to enable the indoor fueling QRA work for NFPA 2, discussed in the previous presentation. NFPA provides guidance for implementing risk assessment in the C&S development process, but the NFPA guidance does not require a particular analysis method, analysis goal, or risk criteria.
There were several features required in a tool to enable QRA for indoor fueling. The tool needed to implement hydrogen-specific models and data, and it needed to assess both probability and consequences. The tool needed to calculate multiple risk metrics to address different questions relevant to NFPA 2. Previous work developed and documented required pieces of the QRA framework. These pieces include data on the frequency of hydrogen releases, probability distributions for ignition, first-order models for predicting heat flux from hydrogen jet flames, CFD models for predicting overpressure consequences, and models for assessing human harm. However, no tool integrated these pieces into an analysis tool.
The QRA tool developed by Sandia includes modules containing accident scenarios, calculating the frequency of the scenarios, and for calculating the number of fatalities from a given scenario. The tool was developed in Matlab. Dr. Groth's presentation included a detailed description of the purpose, inputs, and outputs of each module.

Breakout Sessions

The purpose of the breakout sessions was to obtain feedback on "version 0" of the hydrogen QRA toolkit and to establish priorities for reaching "version 1." For the breakout sessions, participants were divided into two groups. Group 1 consisted of representatives from hydrogen industry, including code developers and insurers. This group was moderated by Chris LaFleur. Group 2 consisted of representatives from the QRA research community. This group was moderated by Aaron Harris.

Group 1 considered the following questions:

- *How do you intend to use QRA (or, if you are not a user: how would C&S developers want to use QRA?)*
- *What level of detail will help users make an informed decision?*
- *Which risk metrics should be included?*
- *What kind of graphical output?*

Group 2 considered the following questions:

- *Is the current toolkit strategy the right approach? If not, what should change?*
- *What should be the top priorities for the QRA toolkit development in hydrogen? In CNG/LNG? Is there good technical alignment?*

Responses to these questions are summarized below. Key takeaways from the breakout session are reported in the next section.

How would C&S developers want to use QRA?
The participants were interested in using the QRA tool to understand how different design decisions impact the calculated risk. They are more interested in comparing risks from different designs than in the calculated risk values. The participants would be interested in changing inputs such as the configuration of the system (e.g., how many valves), the layout of the facility (including location of the dispenser, the dimensions of the facility, etc). C&S users would prefer to use a "standard" set of QRA models and data; they are not interested in changing the probabilities (e.g., for leak occurrence, component failure, ignition) or in selecting among alternative models (e.g., the probit equations for human harm, pressure decay models).

What level of detail will help users make an informed decision?
C&S users are interested in both qualitative and quantitative QRA results. However, the participants believe that C&S developers will not encode specific numerical risk criteria in the codes, although designers may use risk assessment to demonstrate that that their system/facility exceeds specific requirements. Designers may use QRA to evaluate different possible designs to increase safety margins above those required in the standard.

The participants would also like to see more qualitative output. They are interested in high-level documentation of all hazards associated with using hydrogen fuel cells, not just fire-related hazards. This could be used to help safety analysts and AHJs and ensure that hazards such as asphyxiation are not overlooked, even if they are not addressed quantitatively. One participant noted that this high-level guidance could follow the template of other information generated by the National Renewable Energy Laboratory's (NREL) AHJ education project.

Which risk metrics should be included?

Participants supported the use of FAR as a metric for expressing human fatality risk. They also indicated that other users may be interested in the ability to estimate other risks that can be expressed in terms of cost.

What kind of graphical output should be included?

Participants would like to see plots of FAR vs. ALARP limits. Participants also indicated a desire for charts or tables that help compare the risk of hydrogen to the risk of other fuels, such as LNG. However, they realize this may be difficult to implement due to lack of data on other systems.

Is the current toolkit strategy the right approach? If not, what should change?

The participants indicated that the current tool is going in the right direction and will have value to the community. The participants collectively agreed that there are effectively two user communities – the "User" community, who are concerned with using the published versions of the toolkit for purposes such as C&S development, design optimization, code variance justification, etc. The "USER" community needs a toolkit that is trustworthy and prohibits them from making mistakes out of ignorance to the QRA nuances. The other community is a "DEVELOPER" community made up of researchers and government regulators who have an interest in either improving the toolkit or using the toolkit with no prohibitions on the selection of toolkit options.

With regard to the "DEVELOPER" community, there are many detailed consequence models available, but very few of these can produce rapid results with a reasonable amount of fidelity. According to the participants, NFPA is particularly interested in risk-informed code development and this type of tool could facilitate that process. The tool should be increasing leveraged in the code process if success is demonstrated in specific codes.

The participants indicated a strong desire for more alignment of this project with related international research efforts. There is strong hydrogen fuel cell research and development (R&D) happening in Canada, Europe, Japan, and China. The participants specifically suggested engaging with researchers from KIT, HySafe, and IEA HIA Task 31.

The participants indicated that the international research community must be involved in the development ("Developers") of the tool to facilitate acceptance and use of the tool. Organization such as HySafe could play the role of the custodian of the toolkit, in between published versions, to enable better international coordination. Code developers, facility designers, and other analysisists will be more receptive to a toolkit if they are able to provide insight into the tool, either directly or through their trusted research organizations. Teaming with the international community could also enable division of responsibilities. The international community should be leveraged to help select, evaluate and validate the models used in the toolkit.

What should be the top priorities for the QRA toolkit development in hydrogen?
Accurate and relevant data collection was identified as a key priority. The participants would like to see realistic, real world data incorporated as much as possible. Specific sources of data may include:

- Component failure data and incident reports from the NREL composite data center (CDP); both from Technology Validation and American Recovery and Reinvestment Act (ARRA) forklift projects represent a source of relevant data. Current format of the CDP and some restrictions on the data handling prevent this data from being directly incorporated into QRA. Participants in the industry expressed displeasure with what is perceived as a bureaucratic barrier. The concept of collaboration with NREL researchers is strongly suggested.
- Incident reports and root cause data incident databases such as H2Incidents.org or HIAD; participants discussed the benefits and challenges with use of self-reported incident data, however the incidents themselves represented sufficient evidence of relevant failure modes which should not be exempted from consideration.
- Industry groups such as CGA and code development committees such as CSA HPIT 2 may be able to facilitate asking member organizations to provide 'sanitized' data for use by the toolkit.

The participants also suggested increased engagement with the code organizations, especially NFPA, ISO, ICC. Engaging with these groups as soon as possible can help gain an audience for the tool. Furthermore, working with regulations, codes and standards developers can ensure that the toolkit will meet their future needs. The participants cited the example active mitigation (such as leak detection with automatic shutoffs); active mitigation is widely practiced, however separation distances and classified zones required by codes are not reduced when active mitigation is used. This discourages rather than encourages such safety systems. The challenge for the code development committee is accurately quantifying the benefit of these active mitigation systems. Use of the toolkit to appropriately quantify the benefits could allow the committee a scientific basis for modifying the code.

Key Takeaways: QRA Tools for Hydrogen Fuel Cell Industry Analyses

Key Takeaway: **There are two distinct uses for the proposed toolkit: Users and Developers.** Some caution and design effort should go into planning to address each community. Independent custodians of the toolkit can facilitate development and use for the two communities. US DOE domestic stakeholders (such as the NFPA 2 code committee or state fire marshals) could use versions published by US DOE, which include sufficient limitations to prevent misuse. Meanwhile an open-source, "crowd-sourced" development effort could be hosted by HySafe. Many configurations or arrangements of custodianship are possible but the separation of the use communities, Users and Developers, is the chief concern.

Key Takeaway**: C&S users prefer tools that facilitate relative risk comparisons** rather than tools that provide high-fidelity numerical results or tools that provide flexibility in selection of computational models. Toolkit users are likely to sacrifice accuracy of calculated risk for more detailed qualitative insights into ways to improve system design or add features to reduce and mitigate risk. Relative risk comparison is a recurrent theme with the stakeholders, both within the system for design tradeoffs as well as comparison with other fuels or similar human exposures (e.g., from fueling CNG or gasoline vehicles).

Key Takeaway: **Developers must work with code development committees closely to identify opportunities to use the toolkit.** Engaging with these groups as soon as possible can help gain an audience for the tool. Furthermore, working with regulations, codes and standards developers can ensure that the toolkit will meet their future needs. Developers should consider close collaboration with outreach activities sponsored by DOE SCS subprogram such as NREL's outreach AHJs.

Key Takeaway: **Datasets must be developed specifically for use in the toolkit.** The importance of including meaningful, representative data in the toolkit was a recurring theme during the discussions. However, many of the data sources developed to date for the hydrogen safety community cannot be integrated into the toolkit due to issues with data quality and availability. Developers must collaborate with data-collection organizations to ensure that data are of sufficient fidelity to be used in the toolkit. Industry groups may be able to facilitate data availability by collecting and sanitizing data for use in the toolkit.

Expectations for a QRA Tool

The participants gathered at the end of the workshop to consolidate thoughts into the following key criteria for the QRA toolkit and recommended actions for the toolkit development team:

1) *"Open Source"* – develop a toolkit which is not protected by patents, capable of operating in many software packages, capable of being updated by multiple developers, shared without copyright protections and enhances the research collaboration of the hydrogen safety community. The program, Chemkin, was cited as an example.
2) *Communication* - Identify opportunities to communicate regarding the toolkit development
    i. HyIndoor / HySafe Workshop
    ii. NFPA 2 Committee meeting
    iii. ICHS
    iv. IJHE Article
    v. HIA Workshop
3) *Publication Goal* - Meet the community needs by producing Version 1 of the toolkit in the next calendar year with sufficient caveats for accuracy and availability to USER community
4) *Audience* - Create two distinct communities, "USERS" and "DEVELOPERS" with the following criteria for each community:
    a. USERS
        i. Use discreetly published versions of finished QRA toolkit
        ii. Prevent misuse by novice USERS by prohibiting functionality of the algorithm, allow USERS to modify system design parameters to optimize risk, create defaults scenarios and risk metrics.
        iii. Allow USERS qualitative insight options to facilitate relative comparison of options.
        iv. Include training for USERS with sufficient USER manuals, etc.

v. Phase the roll-out of the USER tool by providing access to expert users for novice USERS

vi. Create many USER outputs: FAR, Toolkit Manual, Expected Value, Relative Risk (bubbles and visual relative representations), Importance Measures – relative risk will require multiple candidates or scenarios or components, design tradeoff analysis

vii. Establish methodology for articulating results which facilitates the relative estimates provided by "word results" (i.e. minor, major, etc.) and numerical results

viii. Solicit beta USER volunteers from the code development community and other stakeholders

ix. Balance the fidelity of the model components with the accuracy/robustness of the input data (particularly frequency data)

b. DEVELOPERS

   i. Create a DEVELOPER community with a philosophy of collective ownership. Constituents should include QRA, consequence modeling (combustion) and other research experts who collaborate on revisions of the toolkit. The DEVELOPERS work between versions.

   ii. Include the global community with activities already in process and the concepts or other efforts in toolkit development

   iii. Use the Toolkit "map" as a template for the natural groups for coordination of toolkit components

   iv. Establish timeline for delivery of toolkit component revisions to the next "USER" version

   v. Establish a harmonization group that has objective of improved methods for system design and mitigation strategies

   vi. Leverage the international work in vetting models for use by the toolkit

5) *Data*

a. Identify accident scenarios

b. Quantify accident scenarios

   i. Release frequencies – leaks, accidents, etc.

   ii. Ignition probabilities

   iii. Detection

   iv. Isolation

c. Physical consequence

   i. Gas dispersion

   ii. Radiative heat transfer

   iii. Overpressures

      1. Confined space

      2. Propagation in open

   iv. Release characteristics

d. Potential Resources

   i. NREL Hydrogen Secure Data Center collaboration

   ii. HIA collaboration to access data in Europe

   iii. Elicit data from industry participants – use "check and see" approach to determine a 'generic' input value
   iv. Consider order of magnitude estimates of the "denominator" to get better validation of release frequencies and ignition

6) *Terminology*
   a. Identify a standard and enhance those standards where gaps exist – some participants suggested use of the ISO/IEC guide.

5. CONCLUSIONS AND NEXT STEPS

The objective of the workshop was twofold: (1) Present a methodology and toolkit (currently under development) for conducting QRA to support the development of codes and standards and safety assessments of hydrogen-fueled vehicles and fueling stations, and (2) Improve understanding of the needs of early-stage users (Hydrogen, CNG, and LNG) and set priorities for "Version 1" of the toolkit in the context of the commercial evolution of hydrogen fuel cell electric vehicles (FCEV). The workshop consisted of an introduction and three technical sessions: Risk Informed Development and Approach, CNG/LNG Applications and Introduction of a Hydrogen Specific QRA toolkit

The Risk Informed Development and Approach session provided much needed summary of past work. Until this workshop this work was spread across multiple publications and presentations. This single summary is a useful reference in the effort to continue the toolkit development.

The CNG/LNG Applications session provided insight into the potential benefits of this work to a broader audience. In particular, the immediate needs of organizations such as the DOT to assess the risks in the rapidly evolving CNG/LNG.

The presentation and subsequent feedback from the attendees in the final session revealed many topics and recommendations for consideration in the further development of the toolkit. These recommendations were compiled as a list of expectations from a QRA toolkit.

The participants recommended that the team identify two audiences or user groups: one group, called "USERS" are non-experts who will use the toolkit for codes and standards development, system design and other technology deployment activities. The second group, "DEVELOPERS" is the existing international research community who are concerned with consequences such as deflagrations, QRA methodology and other RD&D topics. These communities are distinctly different and should be incorporated appropriately to enhance the toolkit development. The conclusions section provides detailed list of recommended actions.

Additional recommendations or "key takeaways" are detailed in each section. Key takeaways from the workshop discussions include:

- *Key takeaway*: Current QRA tools lack validated models and data for hydrogen fuel cell analyses.
- *Key takeaway*: There is a critical need for tools that help enable two types of analysis: high level generic insights for C&S developers, regulators, etc., and a detailed tool for site-specific QRA for system designers, AHJs, etc.
- *Key takeaway*: There are relevant parallels between the LNG/CNG and H2 industries.
- *Key takeaway*: Both LNG/CNG and H2 industries can benefit from the collection of incident data.
- *Key Takeaway*: There are two distinct uses for the proposed toolkit: USERS and DEVELOPERS.
- *Key Takeaway*: C&S users prefer tools that facilitate relative risk comparisons.
- *Key Takeaway*: Developers must work with code development committees closely to identify opportunities to use the toolkit.

- *Key Takeaway*: Datasets must be developed specifically for use in the toolkit

The project team plans to establish a working group with stakeholders who have identified willingness to participate. This working group will provide insight and feedback through regular updates and technical review of the QRA toolkit Version 1 progress. The working group will also advise on the strategic aspects of publishing and promulgating the toolkit.

When Version 1 has reached a stable state, the project team plans a review by ‘beta users’ to identify bugs and errors in the algorithm.

It is recognized that a polished software package is the ideal method for promulgating the algorithm. The project team remains unclear on the best approach to developing such software. The generosity of stakeholders to support the full development of this effort will be critical to its success.

APPENDIX A: ABBREVIATIONS AND ACRONYMS

AHJs: Authorities Having Jurisdiction
ALARP: As Low As Reasonably Practical
ARRA: American Recovery and Reinvestment Act
BIV: Business Interruption Value
C&S: Codes and Standards
CDP: Composite Data Center
CNG: Compressed Natural Gas
CVEF: Clean Vehicle Education Foundation
DOE: Department of Energy
FAR: Fatal Accident Rate
FCEV: Fuel Cell Electric Vehicles
FMEA: Failure Mode and Effects Analysis
FRA: Federal Railorad Administration
FRI: Fire Risk Index
GM: General Motors
H2: Hydrogen
IEA: International Energy Agency
LNG: Liquified Natural Gas
NFPA: National Fire Protection Agency
NFPA2: Hydrogen Technologies Code of the National Fire Protection Agency
NREL: National Renewable Energy Laboratory
PRD: Product Requirements Document
QRA: Quantitative Risk Assessment
R&D: Research and Development
RD&D: Research, Development, and Demonstration
RIDM: Risk Informed Decision Making
SCS: Safety, Codes, and Standards
US DOT: US Department of Transportation

APPENDIX B: INDEX

APPENDIX C: WORKSHOP AGENDA

QRA Workshop Agenda

Co-hosted by Sandia National Laboratory and HySafe

June 11-12, 2013

In Person Location: Energetics Incorporated
901 D St. SW, Suite 100
Washington DC, 20024
202-479-2748
Hotel and Travel Information provided in the attached document

Online Conference Link: http://vsecorp.adobeconnect.com/qra/

Teleconference numbers:

Tuesday, June 11: 202-287-6317

Wednesday, June 12: 202-287-6279

Admin POC: Kristine Babick Kristine.Babick@EE.Doe.Gov (202) 406-4139

Sandia Hosts: Aaron Harris apharri@sandia.gov (Cell: 603-852-2914)
Katrina Groth kgroth@sandia.gov (Desk: 505-844-6766)

Purpose of the Workshop:

(1) Present a methodology and toolkit (currently under development) for conducting Quantitative Risk Assessment (QRA) to support the development of codes and standards and safety assessments of hydrogen-fueled vehicles and fueling stations, and

(2) Better understand the needs of early-stage users (Hydrogen, CNG, and LNG) and set priorities for "Version 1" of the toolkit.

Pre-Workshop Reading Materials:

Groth, K. M., J. LaChance, A. Harris. "Design-stage QRA for indoor vehicular hydrogen fueling systems" ESREL-European Safety and Reliability Engineering Conference (2013 Submitted)

Groth, K. M., C. LaFleur, "Risk Assessment Terminology"- Unpublished workshop material

Groth, KM, J. LaChance, A. Harris. "Early-Stage Quantitative Risk Assessment to Support Development of Codes and Standard Requirements for Indoor Fueling of Hydrogen Vehicles" Sandia Report – SAND2012-10150

LaChance, J., W. Houf, B. Middleton, L. Fluer. "Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards" Sandia Report – SAND2009-0874

Tuesday, June 11, 2013

9:00 – 9:15 Introductions & Logistics (Groth/Harris)

9:15 – 10:00 Development of the Risk-Informed Approach (LaChance & Tchouvelev)

10:00 – 10:15 US DOE Welcome (Erika Sutherland)

10:15 – 10:30 *Break*

10:30 – 11:15 Application of Risk-Informed Approach (LaChance & Tchouvelev)

11:15 – 12:00 Recommendations for H_2 QRA Based on CNG (Mohammed Modarres)

12:00 – 1:00 *Lunch (Nearby restaurants, no host)*

1:00 – 1:20 QRA Use in Industry (Chris LaFleur)

1:20 – 2:00 Toolkit User Panel – ***Assessment of Risk Analysis Status Today***

- Hydrogen Safety (Bill Fort – US DOE Safety Panel)
- Hydrogen Station Design (Pete Steiner - Air Products)
- Underwriting (Kumar Bhimavarapu – FM Global)

2:00 – 3:15 Guided Discussion (Harris/Groth)

- ✓ *What questions would you like QRA to answer?*
- ✓ *What problems would you like QRA to solve?*
- ✓ *Is available tools satisfactory for use in the hydrogen industry?*
- ✓ *Is a QRA toolkit necessary for the hydrogen industry in 2-3 years?*

3:15 – 3:30 *Break*

3:30 – 4:30 Toolkit User Panel – ***Potential Benefits of H_2 QRA Activities to CNG/LNG***

- Railcars (Melissa Shurland – US DOT, FRA)
- Repair Facilities (Doug Horne – Clean Vehicle Foundation)
- ✓ *How can the CNG/LNG community use the QRA approaches developed for H2?*
- ✓ *How does CNG/LNG change the approach of QRA toolkit development?*

4:30 – 5:00 Identify Key Takeaways and Priorities

6:30 *Dinner (Hosted by HySafe)*

<u>Wednesday, June 12, 2013</u>

9:00 – 10:00 Introduction to Sandia QRA tool (Groth)

10:00 – 10:15 *Break*

10:15 – 10:45 Toolkit User Panel – ***Expectations for a QRA Tool***

- Codes and Standards Perspective on QRA (Carl Rivkin - NREL)
- Applications of QRA Toolkit Under Consideration (Aaron Harris – Sandia)

11:15 – 12:00 Breakout session: Responses to the tool. (2 groups, assigned by hosts)

Moderators: Chris LaFleur, Jay Keller, Andrei Tchouvelev

- ✓ *Is the current toolkit strategy the right approach? If not, what should change?*
- ✓ *What would make the tool most useful? What would prevent you from using this tool?*
- ✓ *What should be the top priorities for the QRA toolkit development in hydrogen? In CNG/LNG? Is there good technical alignment?*

12:00 – 1:00 Report Out (10 min/group, 30 min organize and prioritize)

1:00 – 2:00 *Lunch (Nearby restaurants, no host)*

2:00 – 3:00 Workshop Wrap-up (summarize, identify keys concepts, and prioritize)

APPENDIX D: WORKSHOP PARTICIPANT LIST

Name	Affiliation
Kumar Bhimavarapu	FM Global
Dave Farese	Air Products
Bill Fort	Hydrogen Safety Panel
Alejandro Gonzalez	Kryogenifex
Katrina Groth	Sandia National Laboratories
Aaron Harris	Sandia National Laboratories
Doug Horne	Clean Vehicle Education Foundation
Will James	US Department of Energy
Jay Keller	Zero Carbon Energy Solutions
Jeff LaChance	Sandia National Laboratories
Chris LaFleur	Sandia National Laboratories
Mohammad Modarres	University of Maryland
Nha Nguyen	US Department of Transportation/NHTSA
Phani Raj	US DOT Federal Railroad Administration
Melissa Shurland	US DOT Federal Railroad Administration
Pete Steiner	Air Products
Erika Sutherland	US Department of Energy
Andrei Tchouvelev	AVT / HySafe
Steve Tucky	CSA Group

Provided supportive responses and participating in future workshops:
Laura Hudy – GE
Anna-lis Laursen – GE
Sidone Ruban – Air Liquide
Béatrice L'Hostis - Air Liquide
Knut Nurdheim – Linde
Glenn Mahnken – FM Global
Gerd Petra Haugmon – DNV
John Boyle – John Boyle Consulting, LLC.
Gerhard Achtelik – CARB
Mike Kashuba – CARB
Chris Ainscough – NREL (National Renewable Energy Laboratory)
Angela Das – PowerTech
John Cornish – Cornish Associates
Bob Boyd – Boyd Hydrogen
Marty Gresho – FP2Fire
Larry Fluer – Fluer Associates

Dick Kauling – GM Canada
Pete Ehlers – CSA Group
Matt Forest – Daimler
Jesse Schnieder – BMW
Steve Mathison – Honda
Spencer Quong – Quong Associates
Jennifer Hamilton – CAFCP
Hans Pausman –Texas A&M University
Thomas Jordan – KIT
Pierre Benard – Univ. of Quebec a Trois Rivieres
Tim Brown – UC Irvine
Frank Markert – DTU
Carl Rivkin - NREL

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