SANDIA NATIONAL LABORATORIES HYDROGEN SAFETY, CODES & STANDARDS PROGRAM

QUARTERLY PROGRESS REPORT FOR JANUARY 2011–MARCH 2011

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FY 2011 MILESTONES/DELIVERABLES

Note: Shaded tasks indicate those impacted by reduced funding levels.

Task	Planned	Status
Task 1—Hydrogen Behavior		
Subtask 1.1—Liquid Hydrogen Behavior		
Complete SAND report on small-scale cryogenic leak measurements of jet H_2 concentration and temperature needed for model validation.	9/11	
Complete SAND report on high-momentum cryogenic jet measurements of H_2 concentration and temperature needed for model validation.	9/11	
Complete large-scale cryogenic release experiments. At reduced funding level, the milestone is deferred.	6/11	Deferred/descoped
Subtask 1.2—Ignitability of Unintended Hydrogen Releases		
Complete high-momentum ambient temperature jet measurements of H_2 concentration and jet exit shock structure for model validation.	11/10	In progress; expected completion 5/11
Acquire velocity measurements from small-scale ambient jets, needed to determine if flame quenching or light-up will occur after an ignition kernel develops in the jet.	12/10	In progress; expected completion 9/11
Complete SAND report on ignition and flame light-up boundaries for high-momentum ambient temperature jets.	2/11	In progress; expected completion 9/11
Map out ignition and flame light-up boundaries for small-scale cryogenic leaks.	5/11	Deferred due to experimental delay
Map out ignition and flame light-up boundaries for high-momentum cryogenic leaks. At reduced funding level, the milestone is deferred.	6/11	Deferred/descoped
Determine flame light-up boundaries for combustible clouds created during large-scale stack venting of LH_2 storage vessels. At reduced funding level, the milestone is deferred.	6/11	Deferred/descoped
Evaluate risk associated with static charge as a source of spontaneous ignition of H_2 jets and document in a SAND report. At reduced funding level, the milestone is deferred.	12/10	Deferred/descoped
Design and implement experimental study to determine the probability of H_2 auto-ignition induced by static charge of entrained particles impinging on the ground. At reduced funding level, the milestone is deferred.	8/11	Deferred/descoped
Design and initiate detailed test plan to experimentally examine diffusion ignition from a burst disk release at typical H_2-fuelled vehicle pressures. At reduced funding level, the milestone is deferred.	8/11	Deferred/descoped

Task	Planned	Status
Subtask 1.3—Hydrogen Refueling		
Obtain data and perform model validation of fast-fill model.	3/11	In progress; delayed to 6/11
Provide analysis to the SAE J2601 committee to inform refueling protocol development.	3/11	
Task 2—Scenario Analysis, Risk Assessment		
Subtask 2.1—ISO/ICC/NFPA/NHA/HIPOC/SAE Interface		
Participate in ISO, NFPA, IC, HIPOC Codes and Standards organizations Task Groups and provide the latest scientific experimental and modeling results from Sandia for use in H_2 Codes and Standards Development.	9/11	
Support NFPA-2 efforts to develop risk-informed separation distance tables for liquid hydrogen facilities.	9/11	
Subtask 2.2—Risk Evaluation and Risk Management		
Prepare a draft report proposing a consensus hydrogen ignition probability model for use in QRA.	9/11	
Complete risk assessment of indoor fuel cell vehicle operations in warehouses and document results in a SAND report.	12/10	Draft in progress; expected completion 6/11
Complete risk assessment of hydrogen releases in residential garages and document results in a SAND report. At reduced funding level, the milestone is deferred.	9/11	Deferred/descoped
Complete risk evaluation of hydrogen refueling stations that utilize liquid hydrogen, steam reformers, or electroyizers as the means of generating hydrogen and document in a SAND report. At reduced funding level, evaluation and documentation of hydrogen generation methodologies will be limited to liquid hydrogen.	6/11	Deferred/descoped
Perform risk evaluation of hydrogen infrastructure and document in a SAND report.	9/11	
Perform risk assessment of metal hydride storage systems and document in a SAND report. At reduced funding level, the milestone is deferred.	3/11	Moved to Storage AOP
Subtask 2.3—Partially Enclosed Releases		
Evaluate risk associated with H_2 releases from a fuel-cell vehicle in a tunnel and document in a SAND report.	12/10	Complete; WHEC and ICHS papers written
Develop engineering model for hydrogen releases in large warehouse-type buildings resulting from indoor refueling-type applications and perform parameter studies.	12/10	In progress; expected completion 5/11

Task	Planned	Status
In conjunction with NFPA-2 and others, define scenarios, baseline cases, and parameters for analysis of hydrogen release from fuel cell backup power systems.	2/11	In progress; expected completion 5/11
Complete analysis of baseline fuel cell backup power system cases: (a) dispersion of unignited hydrogen plume and (b) overpressure and radiative heat transfer from ignited hydrogen plume from storage building vents. Perimeters around storage building required for safety based on lean ignition limits in case (a) and radiative heat flux levels and overpressure in case (b) will be communicated to NFPA-2. At reduced funding level, the milestone is descoped to perform only scoping calculations.	7/11	
Develop engineering models for hydrogen releases and deflagration in parking structures and garages; gather and compare with available experimental data. At reduced funding level, the milestone is deferred.	9/11	Deferred/descoped
Subtask 2.4—Engulfing and Impinging Fire of Hydrogen-Powered Industrial Trucks At reduced funding level, the subtask is deferred.		Deferred/descoped
Subtask 2.5—Advanced Storage Technologies		
Perform experimental assessment of metal hydride-containing systems for storage of H_2 (inform NFPA-2 effort).		Moved to Storage AOP
Recommend insulation and pressure relief placement for metal hydride containers on industrial powered trucks (CSA). At reduced funding level, the milestone is deferred.	9/11	Deferred/descoped
Subtask 2.6—Mitigation Feature Analysis		
Define analysis parameters (with input from NFPA-2 and others) for ventilation and pressure relief for partially confined spaces. At reduced funding level, the milestone is deferred.	9/11	Deferred/descoped
Define analysis parameters (with input from NFPA-2 and others) for H_2 sensor placement within buildings.	9/11	
Define analysis parameters and scenarios (with input from NFPA-2 and others) for water deluge as a hydrogen fire mitigation measure in buildings.	9/11	
Subtask 2.7—Risk Mitigation R&D Priorities		
Identify top 2 technology development efforts that could significantly impact safety from a risk perspective.	9/11	Deferred/descoped
Task 3—Hydrogen Compatible Materials and Components		
Subtask 3.1—ASME/CSA/Materials Interface		
Provide analysis and data in support of code and standard development process.	As needed	

Task	Planned	Status
Report outlining status and R&D needs in high-priority code development processes.	09/11	
Subtask 3.2—Technical Reference for Hydrogen Compatibility of Materials		
Issue 2nd Edition of SAND report representing updated content on website.	12/10	In progress; expected completion 5/11
Subtask 3.3—Materials Testing: Develop Capability for Variable-Temperature Testing in High-Pressure Hydrogen Gas		
Complete collaboration agreement with external partner in conjunction with LVOC capability.	09/11	
Subtask 3.4—Materials Testing: Hydrogen-Assisted Crack Propagation		
Draft of report on development of rising-displacement fracture threshold test method for ferritic steels.	03/11	Not started; expected completion 9/11
Draft of peer-reviewed publication on effects of displacement rate on rising-displacement fracture thresholds for stainless steels. At reduced funding level, the milestone is deferred.	12/10	Deferred/descoped
Draft of report on fracture measurements of aluminum alloys in hydrogen gas. At reduced funding level, the milestone is deferred.	06/11	Deferred/descoped
Subtask 3.5—Materials Testing: Hydrogen-Assisted Fatigue Crack Growth		
Present results on optimizing measurements of fatigue crack growth rates of ferritic steels at quarterly ASME meeting.	03/11	Complete
Draft of report on effects of load-cycle frequency on fatigue crack growth rates for 316 stainless steel at room temperature. At reduced funding level, the milestone is deferred.	09/11	Deferred/descoped
Draft of report on effects of load-cycle frequency on fatigue crack growth rates for 7XXX aluminum alloys.	06/11	
At reduced funding level, initiate testing to evaluate effects of load-cycle frequency on fatigue crack growth rates for 7XXX aluminum alloys.	09/11	
Subtask 3.6—Materials Testing: Hydrogen-Assisted Fatigue Crack Initiation and Growth		
Present results on measurements of fatigue crack initiation in stainless steel at ICHS 2011.	09/11	
Subtask 3.7—Application of Hydrogen Compatible Materials		
Present tank testing and code development results for lift trucks at ICHS 2011.	09/11	

Task	Planned	Status
Subtask 3.8—Fatigue-life of Composite Materials and Components At reduced funding level, the subtask is deferred.		Deferred/descoped

INTRODUCTION

Sandia National Laboratories provides the technical basis for assessing the safety of hydrogen-based systems with the accumulation of knowledge feeding into the modification of relevant codes and standards. The project consists of four components: (1) scenario analysis and risk assessments for safety, (2) hydrogen-compatible materials, (3) hazards mitigation technologies for hydrogen applications, and (4), codes and standards advocacy. Sandia provides the technical guidance and management for this task; however, it is executed in concert via collaborations with universities, national laboratories and other research institutions, professional organizations such as the ASME, CSA, ICC, NFPA, NHA, HIPOC, SAE, and international collaborations through the IEA, IPHE, and the EU.

This project is a cornerstone for the development of safe hydrogen systems as dictated in Section 3.7 and 3.8 of the 2007 issue of the Hydrogen, Fuel Cells and Infrastructure Technologies Program (HFCITP) *Multi-Year Research, Development and Demonstration Plan* (MYRDDP). In addition, this program impacts all areas of the hydrogen fuel initiative, including delivery (Task 4 in Table 3.2.3), storage (Task 1 and eventually Tasks 2, 3, and 5 in Table 3.3.4), fuel cells (specifically, stationary applications within Tasks 5, 6, 7, and 8 in Table 3.4.15 because those tasks are at risk for unintentional leaks [buoyancy- and/or momentum-driven] that might occur as a result of a faulty part), validation (Tasks 1 and 2 in Table 3.6.2), codes and standards (Tasks 1 and 2 in Table 3.7.6), and safety (Tasks 1 through 4 in Table 3.8.5). The requirement for a materials guide is identified in Table 3.7.5.

The principle barriers being addressed by Sandia Hydrogen Safety, Codes and Standards R&D project consist of barriers N (insufficient technical data), P (large footprint requirements), and Q (parking, tunnels, etc.) as described in the Codes and Standards section of the 2007 MYRDDP.

IGNITABILITY OF UNINTENDED HYDROGEN RELEASES—HIGH SOURCE PRESSURE RELEASES

Extensive analytical and experimental investigations have been carried out to determine the hydrogen leakage behavior from compressed gas storage systems [1–3]. Ignition probability contours have been mapped for laboratory-scale releases of high- and low-momentum, unchoked hydrogen jets using planar laser Raleigh scattering (PLRS) and probabilistic laser spark ignition. Ignition probabilities were found to correlate with the flammability factor (FF), which is the integration of the conditional fuel concentration probability density functions (PDFs) between the lower and upper flammability limits. It was developed by Birch et al. [4] for natural gas and methane jets. Birch and coworkers further measured flame stability limits for high source pressure methane jets [5]. For these types of releases, the exit flow is choked and an underexpanded jet (Fig. 1), characterized by a complex shock structure and non-uniform velocity distribution, forms at the jet exit. Due to the complicated nature of the jet exit flow field, simplified ignition probability predictions typically rely on empirically developed source models to account for the increased effective jet diameter and incompressible jet scaling laws to model the subsonic jet concentration decay.

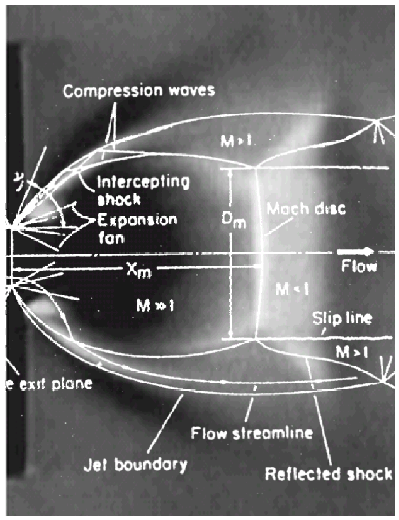

Figure 1. Typical image of an underexpanded jet.

To date, the source model methodology provides satisfactory agreement with experimental measurements [6], but additional data is needed to verify that ignition probabilities continue to correlate with measured FF values. This will be accomplished through schlieren imaging of the jet exit shock structure and instantaneous concentration measurements from PLRS imaging. Ultimately the acquired data will be used to extend and validate the predictive capabilities of the ignition and flame light-up models and will form an important input to the QRA efforts. The results are expected to significantly impact codes and standards decisions in NFPA-2, NFPA 55, and IEA 19.

To support the development of an experimental test facility used to study underexpanded jets from flammable gases, Adam Ruggles and Isaac Ekoto have completed the design and safety certification of a high-pressure gas delivery system that is to be incorporated into Sandia/CA's Turbulent Combustion Laboratory (TCL). The design maximum allowable working pressure (MAWP) of the high-pressure delivery system is 950 psig, which allows for pressure ratios of up to 60:1. A new high-pressure manifold, of which a schematic is shown in Fig. 2, has been designed to supply pressurized hydrogen or methane gas to existing stainless steel laboratory pipe work from externally located compressed storage bottles. A new high-pressure regulator is used to reduce the input gas pressure to the desired working value. The pressurized gas is then directed into a new stagnation chamber and nozzle assembly (Fig. 3) that is used to establish the initial thermodynamic (pressure and temperature) and flow field conditions. Both the stagnation chamber and nozzles have been designed and constructed according to the ASME Pressure Vessel and Boiler Code [7], and have been proof tested for operation up to 1,000 psig. Furthermore, after a basic analysis of hydrogen embrittlement, it was determined that this phenomenon is not a concern for the present setup. All released gases and/or products of combustion are collected by an existing laboratory exhaust system and expelled outside.

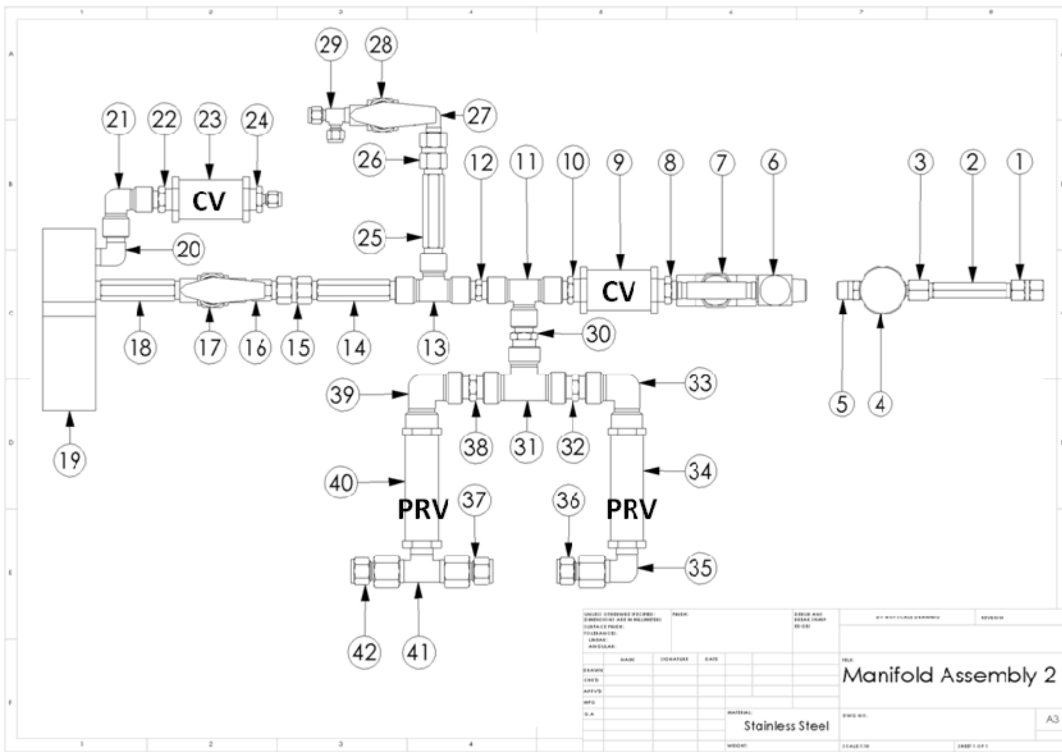

Figure 2. Newly developed gas manifold assembly rated for 950 psig.

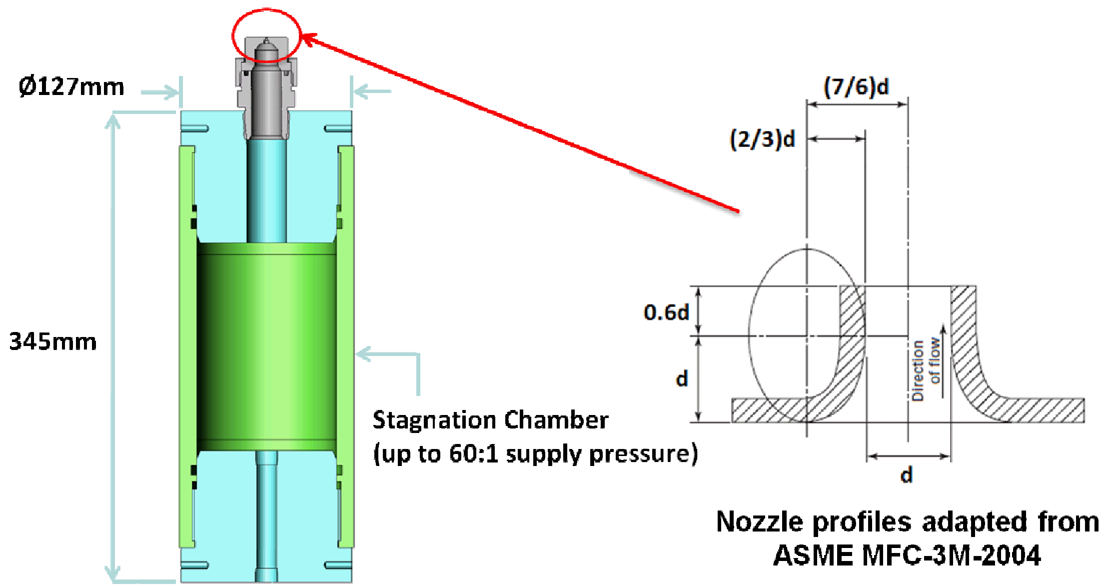

Figure 3. Schematic of the newly built stagnation chamber and nozzle. The apparatus has been proof tested for operation up to 1,000 psig.

A pressure data package that summarizes the specifications of each component has been developed. Furthermore, separate documents that assess the potential flammable envelope and radiation hazards based on the operating conditions have been created. Although the current nozzle diameters are smaller than those used in previous studies (1.5 and 1.0 mm vs. 1.9 mm), the flow rates will be substantially higher due to the elevated supply pressures. Respective hydrogen and methane flow rates can be up to 2,250 and 760 standard liters per minute based on the flame radiation and exhaust system capability hazards. These documents were used to justify the safety of the experiment to an interdisciplinary team of Sandia Environmental Health and Safety (ES&H) experts in Q1FY11, and approval from the ES&H team has been granted. Ongoing coordination between these ES&H experts will be used to address additional safety concerns such as noise from resonant screech tones. Construction of the high-pressure gas supply system is expected to occur in Q2FY11 and initial operation is expected to begin in Q3FY11.

References

[1] Houf WG, Schefer RW, Analytical and experimental investigation of small-scale unintended releases of hydrogen. *International Journal of Hydrogen Energy*, 2008;33:1435-1444.

[2] Schefer RW, Houf WG, Williams TC, Investigation of small-scale unintended releases of hydrogen: momentum-dominated regime. *International Journal of Hydrogen Energy*, 2008;33:6373-6384.

[3] Schefer RW, Houf WG, Williams TC, Investigation of small-scale unintended releases of hydrogen: Buoyancy effects. International Journal of Hydrogen Energy, 2008;33:4702-4712.

[4] Birch AD, Brown DR, Dodson MG, Ignition probabilities in turbulent mixing flows. Eighteenth Symposium (International) on Combustion, The Combustion Institute, 1981, p. 1775-1780.

[5] Birch AD, Brown DR, Cook DK, Hargrave GK, Flame stability in underexpanded natural-gas jets. *Combust Sci Technol*, 1988;58:267-280.

[6] Schefer RW, Houf WG, Williams TC, Bourne B, Colton J, Characterization of high-pressure, underexpanded hydrogen-jet flames. *International Journal of Hydrogen Energy,* 2007;32:2081-2093.

[7] ASME Boiler and Pressure Vessel Code, Section 8, Rules for Construction of Pressure Vessels. In: ASME, ed. 2007.

IGNITABILITY OF UNINTENDED HYDROGEN RELEASES—FUNDAMENTAL IGNITION AND LIGHT-UP PHENOMENA

Science-based codes and standards development for bulk storage and transportation of compressed hydrogen requires a thorough understanding of the consequences of hydrogen release scenarios so that effective quantitative risk assessment (QRA) models can be created. Extensive analytical and experimental studies have already been carried out to investigate leakage behavior from compressed natural gas systems [1, 2]. From these studies, it has been established that ignition boundaries for turbulent methane and natural gas jets correlate well with the flammability factor (FF), which is the integration of the probability density function (PDF) between the fuel flammability limits. Although the FF does not predict the probability of flame light-up, it nonetheless allows CFD modelers to determine the likelihood that an ignition kernel will develop within a given region of the jet.

To verify that the FF concept was applicable to releases from hydrogen bulk storage, Schefer et al. [3] repeated these light-up boundary, ignition probability, and concentration measurements for turbulent hydrogen jets in Sandia/CA's Turbulent Combustion Laboratory (TCL) during FY08. This was accomplished through a combination of laser spark ignition and planar laser Raleigh scatter (PLRS) imaging. These measurements were also performed for methane jets and compared to results from Birch et al. [1]. In contrast to the observations by Birch, it was found that the methane jet maximum axial and radial extents of the light-up boundaries were roughly a third lower. It should be noted, however, that significantly smaller jet exit diameters (1.905 mm vs. 12.7 mm) and Reynolds number (3,406 vs. 12,500) were used for the Sandia study, and these differences may have had an impact on the flow features that control light-up. An additional discrepancy, however, was that the measured FF did not agree well with the ignition probability in the jet far field. Thus, it was concluded that the experimental methodology needed to be refined. In Q4FY10, ignition probability and jet light-up boundary measurements were repeated using the described laser spark apparatus with the following experimental improvements:

1. The number of samples was doubled at each spark location for greater statistical convergence.

2. A higher number of thermocouples were used to more reliably detect the formation of ignition kernels.
3. Air conditioner vents were blocked to minimize air current disruptions to the flow.

With these improvements, the new ignition probability measurements had much better agreement with the previously recorded methane and methane jet FF values. Nonetheless, repeated methane light up boundaries, acquired in Q4FY10, were essentially unchanged from the measurements in [3]; thus it was concluded that the differences in flame light-up boundary relative to the Birch data [1] were primarily driven by flow characteristics.

New FF measurements with the improved experimental setup are still needed to verify trends and supply CFD modelers with needed validation datasets. Last quarter, Adam Ruggles, Jiayao Zhang, and Isaac Ekoto repeated the PLRS measurements for the turbulent methane and hydrogen jets with the experimental setup improvements described above. In Fig. 4, a typical instantaneous image of the turbulent hydrogen jet is shown after laser power fluctuations, optical response, background scatter, and laser sheet intensity were corrected for, and a calibration for pixel intensity was applied. Figure 4 illustrates that the measurement resolution for the instantaneous image was below 1%.

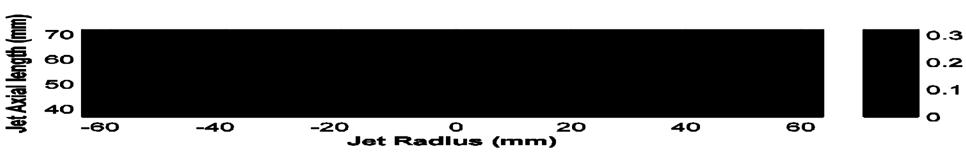

Figure 4. Instantaneous image of concentration for a turbulent methane jet with a Reynolds number of 3,406.

Mean and fluctuating turbulent statistics, derived from ensemble averaged concentration fields, are shown in Fig. 5 for the methane jet along with a contour map of the FF. Within the displayed region of the jet, turbulent statistics follow the well established jet scaling laws, which suggests good measurement fidelity. Further downstream, however, measurement irregularities, attributed to calibration drift, were observed, and additional post-processing corrections are currently being developed and applied. Once satisfactory statistical agreement with classical scaling laws has been achieved, a similar post-processing methodology will be applied to the turbulent hydrogen jet data.

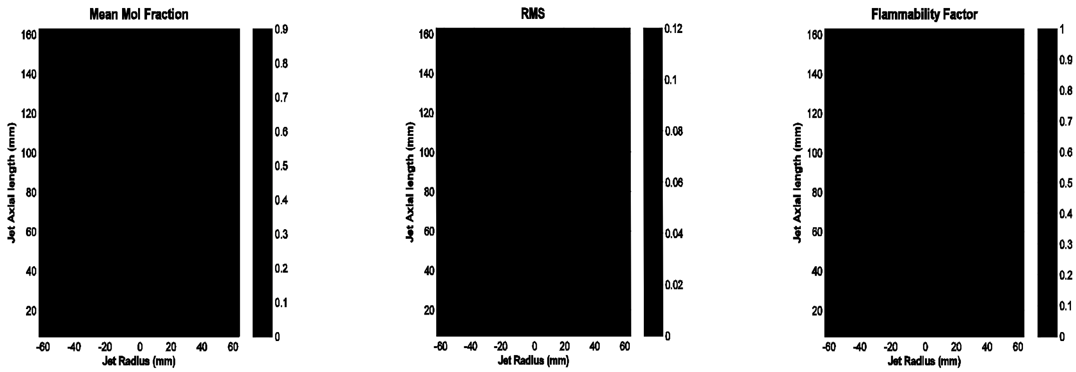

Figure 5. Ensemble averaged contour maps of the mean and fluctuating concentrations for the methane jet, along with the FF.

Centerline FF and ignition probability measurements from 2008 and 2010 are compared in Fig. 6 within the near-field region of the methane jet. The new FF measurements exhibit good agreement with the newly recorded ignition probability measurements, and it is expected that once the far field data is processed, these trends will continue to hold in the downstream region of the jet.

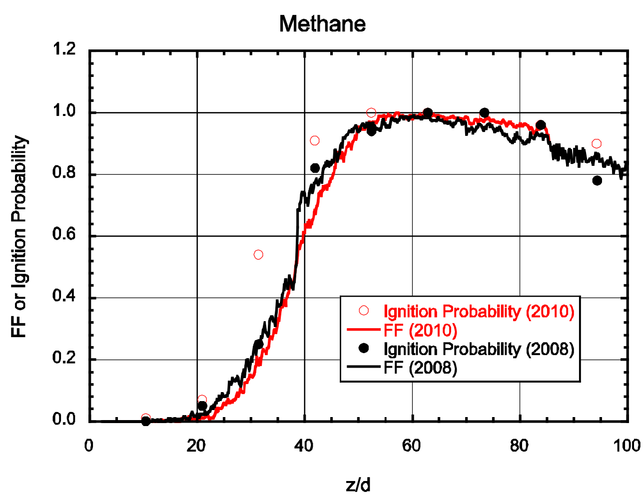

Figure 6. Original and repeated centerline profile measurements of FF and ignition probability.

Good agreement between the FF and ignition probability measurements in the region where flame light-up occurs provides support for the modeling approach adopted by Greg Evans to determine flame light-up boundaries. In FY11, conditional velocity statistics that measure flow strain rates and turbulent stress intensities will be acquired to determine the dominant sustained light up mechanisms.

References

[1] Birch AD, Brown DR, Dodson MG, Ignition probabilities in turbulent mixing flows. Eighteenth Symposium (International) on Combustion, The Combustion Institute, 1981, p. 1775-1780.

[2] Birch AD, Brown DR, Cook DK, Hargrave GK, flame stability in underexpanded natural-gas jets. *Combust Sci Technol*, 1988;58:267-&.

[3] Schefer RW, Evans GH, Zhang J, Ruggles AJ, Greif R, Ignitability limits for combustion of unintended hydrogen releases: Experimental and theoretical results. *International Journal of Hydrogen Energy*, in press.

Unintended Releases of Hydrogen in Partially Enclosed Spaces

Sandia has been working with original equipment manufacturers (OEMs) to develop scientific understanding that will form the basis for risk-informed safety codes and standards for safe operation of indoor hydrogen fuel-cell forklift vehicles. A combined modeling and experimental approach has been used to develop an experimentally validated model for dispersion and ignition of unintended releases from hydrogen forklift vehicles in warehouses. Results of the modeling and experiments were presented to the DOE Technical Team, the Hydrogen Industrial Panel on Codes and Standards (HIPOC), and at the Annual Fuel Cell and Hydrogen Energy Conference during the month of February. Based on feedback from these presentations a new indoor refueling task group is forming within NFPA 2 (National Fire Protection Association) to utilize the experimental data and validated model in a science-based risk-informed process to develop new indoor refueling codes and standards for NFPA 2. As part of this work the validated forklift warehouse release model is being used to study the effect of leak size, ignition delay time, ventilation, warehouse volume, and shelving on the associated hazards. Results of this modeling study will be used in a risk analysis that will be utilized by the task group to develop new risk-informed indoor refueling codes and standards. Figures 7 and 8 show results from the parameter study where the validated model has been used to investigate the effect of warehouse volume and ignition delay time on the amount of overpressure produced from ignition of a hydrogen forklift unintended release.

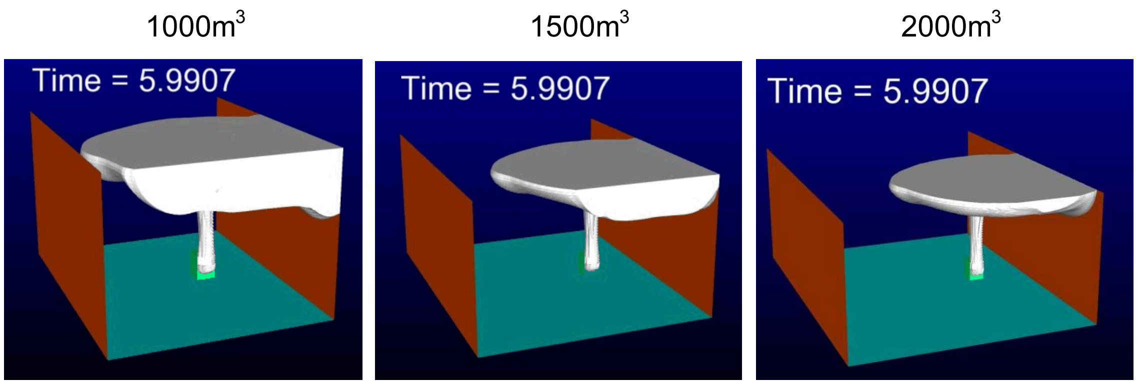

Figure 7. Simulations showing flammable hydrogen cloud (4%–75% mole fraction) 6 sec into the 0.8-kg forklift release for full-scale warehouses with a 7.62-m high ceiling and volumes of 1000 m^3, 1500 m^3, and 2000 m^3 (without ventilation). Initial tank pressure of 35 MPa and a leak diameter of 6.35 mm.

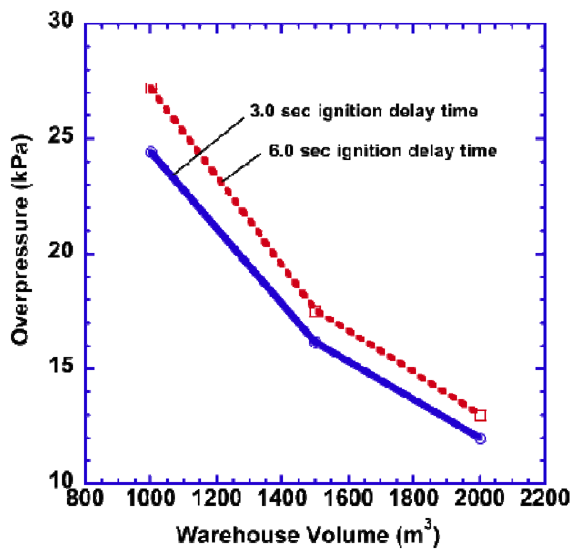

Figure 8. Simulations showing peak ignition overpressure in a well-sealed (100%) full-scale warehouse for a 0.8-kg forklift release where ignition occurs 3 cm above the top of the forklift and the ceiling height is 7.62 m. Results include heat transfer to the warehouse walls and show the effect of changing the ignition delay time and warehouse volume. Initial tank pressure of 35 MPa and a leak diameter of 6.35mm.

References

[1] Houf, W.G., Evans, G.H., Ekoto, I., Merilo, E. and Groethe, M., "Hydrogen Releases and Ignition from Fuel-Cell Forklift Vehicles in Enclosed Spaces," 2011 Annual Fuel Cell and Hydrogen Energy Conference, Washington D.C. Area, February 13–16, 2011.

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[3] Ekoto, I.W., Merilo, E.G., Houf, W.G., Evans, G.H., and Groethe, M.A., "Experimental Investigation of Hydrogen Release and Ignition from Fuel Cell Powered Forklifts in Enclosed Spaces," 4th Int. Conf. on Hydrogen Safety, San Francisco, CA, Sept. 12–14, 2011.

RISK ANALYSIS

Work continued this quarter in two areas associated with quantitative risk analysis (QRA) of hydrogen facilities: (1) support in establishing risk-informed separation distances for International Organization of Standardization (ISO) standard for gaseous hydrogen fueling stations (ISO/IS 20100) and (2) estimation of the risk from indoor refueling.

Efforts to harmonize the ISO and NFPA approaches for establishing separation distances have generally been successful as both used essentially the same risk approach for evaluating separation distances developed by SNL. Similarly, the SNL consequence models and the hydrogen leak data generated by SNL were used in both evaluations, although modifications of the leak frequencies were generated for the ISO risk assessment. The application of the ISO leak frequency distributions in the ISO risk assessment results in lower risk estimates and associated separation distances then would be obtained using the SNL leak frequencies. At the ISO TC 197 WG11 meeting, Jeff LaChance gave a presentation that identifies concerns related to the modification of the SNL data in the ISO analyses in the hopes of better harmonizing the separation distances in the ISO and NFPA standards.

The major concern with the ISO component leak frequencies has been related to the binning of the data used in the SNL Bayesian approach for generating hydrogen-specific leak frequency estimates. A cursory analysis of the generic data by the ISO TC 197 separation distance task leader was utilized in a non-rigorous statistical approach to generate the ISO leak frequencies. The ISO data analysis only utilized a subset of the available generic data, did not include any hydrogen-specific data, and did not evaluate the leak frequencies using a justifiable statistical approach. Instead, the limited review of the generic data was utilized to generate arbitrary, idealized linear (on a log–log plot) versions of leak frequency distributions generated by SNL. In addition, the ISO leak frequencies were essentially shifted an order of magnitude based on the argument that some of the generic data was mis-binned and that a different binning scheme should be utilized.

In an effort to more rigorously evaluate the impact of the data binning performed by ISO and the resulting leak frequencies, Sandia performed sensitivity studies in which both the generic and hydrogen specific data were rebinned, where appropriate, into the binning categories utilized in the ISO risk assessment. The rebinned data was then utilized in a Bayesian analysis to generate estimates of hydrogen component leak frequencies. An example of the results of the Bayesian analysis for valves compared to the corresponding ISO leak frequency distribution is provided in Fig. 9, which illustrates that the rebinning of the generic leakage data for valves does not have a significant effect on the hydrogen leakage frequency profiles generated using the Bayesian process. Although the linear approximation of the SNL-generated leak frequency profile by ISO is reasonable, the shifting of the ISO curve based on different bin definitions is not justified and provides a non-conservative representation of the Bayesian-generated leak frequency distribution. For other components, a review of the data indicated that most of the data was correctly binned and thus the basis for shifting the linearized ISO representations of the SNL data is also not justified.

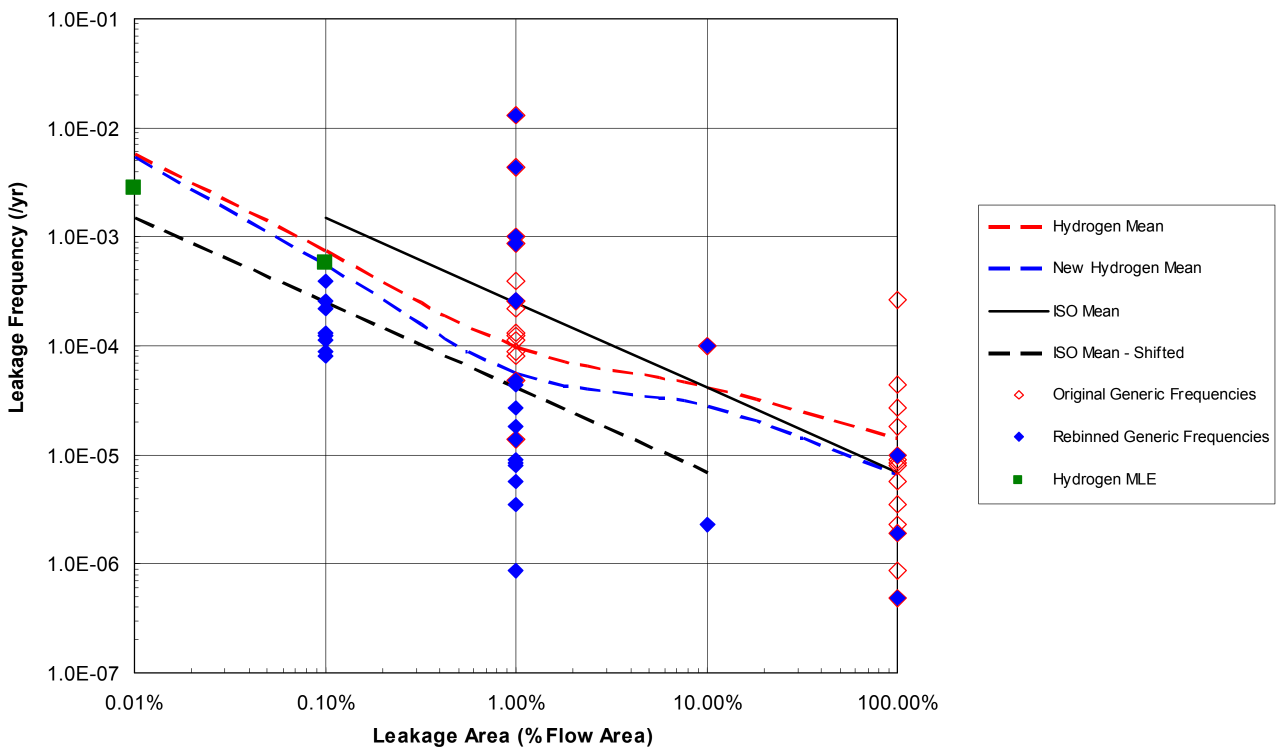

Figure 9. Impact of re-binning valve leak frequency data.

Work is continuing on evaluating the implications of the data simplifications used in the ISO risk evaluation on the resulting separation distances, the associated risk to members of the public, and other ISO/IS 20100 requirements. In addition to the impact of the ISO component leak frequencies, the use of a constant ignition probability in the ISO risk assessment and other simplifications are being evaluated. The results of this effort are documented in a paper to the National Hydrogen Association conference held in February 2011.

Work on indoor refueling during this quarter was focused on obtaining the design and operational information needed to construct a risk model of hydrogen-powered forklift operations. In addition, data collection efforts related to indoor refueling continued through the NREL under the Technology Validation program. Construction and evaluation of the risk model will be performed in the next quarter.

MATERIALS AND COMPONENTS COMPATIBILITY

The fatigue life materials test is considered to be particularly relevant for many hydrogen containment components on fuel cell vehicles. For example, this test has been included in both the CSA CHMC1 and SAE J2579 standards. Fatigue life tests that employ smooth or notched specimens are intended to evaluate the effect of hydrogen on fatigue crack initiation. The output from fatigue life testing is an "S-N curve" for the material, which is a locus of points representing the number of cycles to failure (N) for a constant stress amplitude (S) applied to the test specimen. Generating the full S-N curve in hydrogen gas may be an exceptional burden to laboratory testing capabilities if these tests need to be performed at low load-cycle frequency to accommodate the kinetic steps for hydrogen uptake into the metal. Thus, the materials testing procedure needs to be optimized to enhance test efficiency without compromising data reliability. Sandia has initiated an activity to explore a materials testing methodology that will address fatigue crack initiation and inform the evolving CSA CHMC1 and SAE J2579 standards.

There are two principal objectives associated with the fatigue life testing in this Materials Compatibility task: (1) establish an optimum load-cycle frequency that enhances test efficiency without compromising data reliability and (2) evaluate whether fatigue crack initiation dominates the number of cycles to failure in the fatigue life test. For this latter objective, it must be recognized that the number of cycles to failure (N) consists of the number of cycles for crack initiation (N_i) plus the number of cycles for crack propagation (N_p). Since tests on smooth or notched specimens are intended to evaluate the effect of hydrogen on crack initiation, the ratio of N_i/N should be nearly equal to 1. The first series of tests in this task were intended to establish the N_i/N ratio for a notched specimen geometry that is proposed for the CSA CHMC1 and SAE J2579 standards.

The S-N curve was measured for the austenitic stainless steel 21Cr-6Ni-9Mn (21-6-9). Cylindrical specimens having a circumferential notch were fabricated from the 21-6-9. These specimens were then exposed to 138 MPa hydrogen gas at 300 ^{o}C to create an internal hydrogen concentration of approximately 200 wppm. Specimens of the hydrogen-charged and non-charged 21-6-9 were tested at constant stress amplitudes, and the number of cycles to failure, N, were recorded for each test. The tests were conducted at a load ratio, R (ratio of minimum stress to maximum stress), equal to 0.1 and a load-cycle frequency of 1 Hz. In addition, each specimen was instrumented with an extensometer and the direct-current potential difference (DCPD) system to detect crack initiation. Results showing the number of cycles for crack initiation, N_i, and the number of cycles to failure, N, for both hydrogen-charged and non-charged specimens are summarized in Figure 10.

Two results are notable in Figure 10. First, hydrogen does not have a significant effect on the fatigue life of the 21-6-9 stainless steel. Second, the number of cycles for crack initiation, N_i, is approximately 50% of the total number of cycles to failure. The second observation indicates that the number of cycles to failure measured from the circumferentially notched specimen does not adequately approximate the number of cycles for crack initiation. This insight may influence the specimen geometry that is specified in the CSA CHMC1 and SAE J2579 standards.

Brian Somerday gave the following two invited presentations during FY11 Q2:

- "Addressing Hydrogen Embrittlement in the Fuel Cell Vehicle Standard SAE J2579," B. Somerday, International Hydrogen Energy Development Forum 2011, Fukuoka, Japan, Feb. 2011.

- "Improving the Fatigue Resistance of Ferritic Steels in Hydrogen Gas." B. Somerday, I^2CNER Kick-off Symposium, Fukuoka, Japan, Feb. 2011.

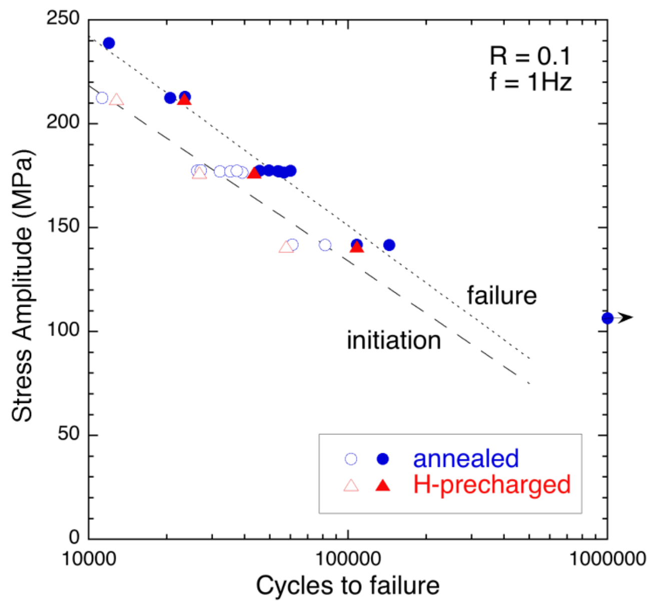

Figure 10. Stress amplitude (S) vs. number of cycles for crack initiation (N_i) and total number of cycles to failure (N) for hydrogen-charged and non-charged 21-6-9 stainless steel.

LIFECYCLE ANALYSIS OF FORKLIFT TANKS

During this quarter, a number of upgrades were made to the testing system to accommodate the cycling of 10 tanks simultaneously; these upgrades included remanufacturing a portion of the compressor that delivers the high-pressure gaseous hydrogen. Concurrent cycling of 10 tanks has been demonstrated, which includes two tank designs (designated as T1 and T2). Three "as-manufactured" tanks of the T1 design have experienced greater than 18,000 cycles, while three tanks (T1) with manufactured defects have experienced greater than 5,000 cycles. Three tanks of the T2 design have been cycled for less than 1,000 cycles due to failures of the O-ring seals (O-ring seals are an important distinguishing characteristic of the T2 design). These seals are being remade. The tenth tank (T1 design) has developed a leak at the primary fitting between the tank and manifold; the leak has been characterized and will be monitored when the tank is returned to the system. In short, the structural integrity has been maintained for all the tanks; as of the end of December 2010, all observed "failures" are believed to be associated with sealing interfaces.

CODES AND STANDARDS ADVOCACY

Bill Houf and Isaac Ekoto participated in HIPOC teleconferences during the last quarter, and Bill Houf and Jeff LaChance participated in an NFPA-2 Task Group 6 teleconferences. Based on input from LaChance and Houf, Task Group 6 has developed a new, simplified version of the gaseous hydrogen separation distance table that was submitted to NPFA 55 this code cycle. Houf and LaChance are also members of ISO/TC 197 WG11 TG1 and worked on the development of a gaseous hydrogen separation distance table that has been submitted to the ISO Code. Houf and LaChance also participated in the IEA Task 19 held in Rome, Italy, on October 4–6, 2010. Houf gave a presentation on recent Sandia work on unintended releases of hydrogen while LaChance reported on risk analysis work done for the ISO code.

Two papers, “Hydrogen Releases and Ignition from Fuel-Cell Forklift Vehicles in Enclosed Spaces,” and “Results from an Analytical Investigation of High-Pressure Liquid Hydrogen Releases,” were accepted for presentation at the Fuel Cell and Hydrogen Energy Conference (Washington, D.C., February 13–16, 2011). Two papers, “Hydrogen Fuel-Cell Forklift Vehicle Releases in Enclosed Spaces,” and “Simulation of High-Pressure Liquid Hydrogen Releases,” have been submitted for presentation at the 4th International Conference on Hydrogen Safety (San Francisco, CA, September 12–14, 2011).

INTERNATIONAL ENERGY AGENCY HYDROGEN IMPLEMENTATING AGREEMENT: HYDROGEN SAFETY

The lack of operating experience with hydrogen energy systems in consumer environments continues as a significant barrier to the widespread adoption of these systems and the development of the required infrastructure. During recent years, a significant international effort has been initiated to develop the necessary codes and standards required for the introduction of these new systems. However, such codes and standards are usually developed through operating experience in actual use that is accumulated over time. Without such long-term experience, there is a natural tendency for such codes and standards to be unnecessarily restrictive to ensure that an acceptable level of safety is maintained. One possible effect is to hinder the introduction of hydrogen systems and thus the operating experience upon which future infrastructure is developed. Likewise, this lack of operating data impacts other areas such as insurance cost and availability and public acceptance.

Although an understanding of hydrogen’s physical properties is well established, and many experimental efforts have attempted to fully characterize the risks and hazards related to hydrogen, the actual risks and hazards can only be determined within the context of real systems and real operating experience. Previous experience with hydrogen has not been with systems that will interface with consumers, but in controlled environments using trained personnel.

Task 31, Hydrogen Safety, was approved for a three-year term by the IEA Hydrogen Implementing Agreement in October 2004, and, after being extended for an additional three years, was completed in October 2010. The results achieved by this collaboration were significant, but the experts unanimously agreed that more work is needed and this can best be accomplished through a new task on hydrogen safety. This annex is the logical follow-on activity to Task 31 and will build on the results of Task 19 to alleviate the issues of hydrogen safety and the lack of uniform Regulations, Codes and Standards to reduce or eliminate these as a barrier to the widespread commercial adoption of hydrogen energy systems.

OBJECTIVE

The objective of this Task is to develop quantitative risk analyses, testing methodologies and data, and other information that will facilitate the accelerated adoption of hydrogen systems.

PROGRESS DURING THE PREVIOUS QUARTER

No expert or Executive Committee meetings occurred during the reporting period. Efforts were directed at preparations for the Spring 2011 experts meeting in Karlsruhe, Germany, April 11–13. In addition to the normal technical exchange, there were a number of important issues to be discussed. The proposal for a task workshop which was presented at the previous Executive committee meeting in Istanbul (November 2010) was discussed, and a plan for raising the necessary funds was discussed. Also, a memorandum of understanding with the International Association for Hydrogen Safety was discussed, and several candidate collaborations were identified.

ACTIVITIES DURING THE NEXT QUARTER

During the next quarter the operating agent will attend the Spring 2011 Executive Committee meeting in Copenhagen scheduled for June 14–15, 2011.