International Energy Agency

Hydrogen Implementing Agreement

Task 31
Hydrogen Safety

FINAL TECHNICAL REPORT

November 30, 2014

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Preface

In 1974, the International Energy Agency created the Hydrogen Implementing Agreement with a mission to accelerate the widespread commercial adoption of hydrogen energy systems. Under that agreement, a task was proposed in April 2004 to conduct a collaborative effort on hydrogen safety to share existing and new research information to alleviate safety-related barriers to the implementation of hydrogen energy systems, especially the lack of uniform Regulations, Codes and Standards. Among those participating were safety experts from more than ten member countries of the Implementing Agreement.

The initial task was approved for a three-year term by the IEA Hydrogen Implementing Agreement in October 2004 and in 2007 was extended for an additional three years to October 2010. The results achieved by this collaboration were significant, but the work plan was ambitious, and the participating experts unanimously agreed that more work is needed and this could best be accomplished through a new task on hydrogen safety. Thus a new task, Task 31, was proposed as a logical follow-on activity to build on the results of Task 19.

The purpose of this report is to provide a technical overview of the two tasks on hydrogen safety to include their original scope, ongoing participation, the evolution of the collaboration, current issues and a discussion of the opportunities afforded by for future collaborations in light of member budgetary constraints and anticipated levels participation.

The collaboration was conducted under a strict policy that all shared information would be subject to a strict vetting policy whereby no information would be published without approval of the participants. Consequently, this report provides limited technical detail of unpublished research results and data shared by the participating experts.

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Acknowledgments

The Operating Agent and the participants of Tasks 19 and 31 would like to acknowledge the invaluable support of the U.S. Department of Energy and Natural Resources Canada to the management of these tasks. In particular, we would like to thank Mr. Nick Beck of Natural Resources Canada, Mr. Neil Rossmeissl of the U.S. Department of Energy and Mr. Antonio Ruiz of the U.S Department of Energy for their leadership in initiating these important technical collaborations on Hydrogen Safety.

The task also thanks the IEA Hydrogen Implementing Agreement Executive Committee members for their on-going support, especially Jan Jensen, Chairman, Mary-Rose de Valladares of the HIA Secretariat and to all participating countries who provided financial support to conduct the work of this collaboration and for expert participation.

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Executive Summary

Since 2004, the International Agency Hydrogen Implementing Agreement has conducted technical collaborations on hydrogen safety through two approved tasks. Eleven member countries participated by attending semi-annual meetings of qualified experts to share information, discuss research data and reach consensus on key issues regarding the priorities and needs to facilitate the development of codes and standards and reduce both the technical and non-technical safety-related challenges to the commercial adoption of hydrogen energy systems.

The collaboration is represented by 26 semi-annual meetings of safety researchers and experts from at least 11 countries. A major thrust of the collaboration was to develop more reliable methods of assessing risk in hydrogen systems and in identifying and obtaining information need to increase the confidence level of such risk assessment methods.

The primary value of this collaboration was the information exchange of unpublished data and discussions to evaluate new research results within the context of the combined experience of the experts. This had the primary benefit of allowing each participating expert to be cognizant of such research and build on it rather that duplicating the efforts of others. This was especially true of the experimental and testing work conducted in several countries, as that work tends to be costly.

In addition to Risk Management and Experimental and Testing, the third focus of the collaboration was the coordination of information products targeted at stakeholder groups, particularly codes and standards developers, regulators and early adopters.

These hydrogen safety collaborations were considered extremely effective until participation at the semi-annual experts meetings was impacted by national program budgets in 2011.

Final Technical Report
IEA HIA Tasks 19 and 31 on Hydrogen Safety
For the period October 2004 through October 2010

1.0 Introduction

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. 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. During recent years, a significant international effort has been initiated for the development of necessary codes and standards required for the introduction of these new systems.

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

1.1 Benefits of International Collaboration and Information Shared

The subject of safety is particularly benefitted by international collaboration. It provides an opportunity for researchers to put their technical objectives and results into the context of the broader research community. Collaboration facilitates reaching consensus among researchers to guide national programs and prioritize technical issues while building upon the experience and results of like and complementary projects. The collaboration is most efficient when unpublished data is freely shared and national programs do not have to replicate similar efforts. Importantly, such collaborative activities facilitate the development of consistent and less restrictive codes and standard among the participating countries.

The collaboration achieved by the participants of Tasks 19 and 31 have resulted in a significant amount of information gained by the U.S. DOE beyond what it has contributed to the collaboration. In addition the in-person meetings allowed the participating experts to share information and for in-depth discussions to gain insights and consensus not achievable by published reports or technical conference presentations. The primary benefits are:

- Easy contact with experts

- Initiation of new collaborations

- Real time up-date of state of the art

- Efficient communication of results and priorities

During the course of this collaboration, several participating countries have modified their national programs to both complement and benefit from work shared.

1.2 Background of the IEA Collaborations on Hydrogen Safety

Although the importance of hydrogen safety as a barrier to widespread use of hydrogen as an energy carrier was recognized, it was not until 2003 that the idea of a separate task be established. An initial task on hydrogen safety was proposed in the Spring 2004, and a Project Definition Phase was authorized to develop a task scope and work plan. Two meetings were held: the first in Washington, DC in June 2004 and a second in Madrid, Spain in the following September. The new task was formally proposed to the Hydrogen Implementing Agreement Executive Committee at their Fall 2004 meeting in London, UK and Task 19 on Hydrogen Safety was formally approved for an initial three-year period. The original three-year term of Task 19 was extended for an additional three years to 2010 when a new Task, Task 31, was approved for a period of three years, (2010-2013).

As with other tasks, the tasks on hydrogen safety were managed by an Operating Agent, and the associated costs were shared equally by two member countries: the United States through the U.S. Department of Energy (DOE), and Canada through Natural Resources Canada, (NRCAN).

During the course of Task 19 and 31 which encompassed the period from October 2004 to October 2013, 10 countries and the European Commission participated:

- Canada
- Denmark
- European Commission
- France
- Greece
- Italy
- Japan
- The Netherlands

- Norway
- United Kingdom
- United States

The collaborative approach represented an efficient means for sharing information and building consensus on technical issues of hydrogen safety. The initial focus of the new task was identify and assess the current state of safety research and risk assessment methodologies and evaluate to what extent they could be applied to hydrogen energy systems. There was extensive information exchange among participating members concerning national programs, funding and priorities to develop a collaborative program that built on existing national programs.

Because of the sensitive nature of the topic of hydrogen safety, potential misuse of unpublished research results and information that could negatively impact public perceptions and acceptance of hydrogen fuels, a well-defined policy was adopted to ensure that confidential or sensitive research data and results shared among members did not become public until properly vetted and approved by all task experts. As a result, a high level of trust was achieved among participating experts resulting in an open sharing of information and the collaboration became an efficient and cost effective way of building on the results of national programs. To ensure that both published and unpublished data was captured and remained conveniently available to the collaboration, a HyTEX database was established at the University of Trois-Riviere, Quebec, Canada, but access to this database remained available only to participating experts.

1.3 Safety Related Challenges to Hydrogen Energy

Hydrogen has been a major industrial commodity for more than five decades, and currently world-wide more than 70 million metric tons per year is produced for use in more than a dozen industries. As fuel cell technology advances and the use of hydrogen fuels has come to the forefront, the public is becoming more aware of its potential as an automobile fuel and heightened concerns about its safety have emerged. Many of the major industrial gas companies have stated that hydrogen can be safely used as a consumer fuel, and a new generation of hydrogen vehicles is scheduled to debut in 2015. Hydrogen is, in certain ways, very different from the current petroleum-based liquid fuels currently in use. Some of these differences pose additional hazards that must be considered, while other properties of hydrogen, such as its high diffusivity, may reduce potential hazards.

At present, hydrogen is safely handled in manufacturing processes for petroleum refining, steel, chemicals, foods, electronics and float glass. It is used to upgrade crude oil to produce cleaner burning gasoline and low sulfur diesel fuel. In the metallurgical industry, hydrogen is used to prevent oxidation when heat-treating certain metals and alloys. Hydrogen is also used by semiconductor manufacturers and in the chemical industry to synthesize ammonia and methanol. Now, hydrogen fuels are poised to assume a key role in the world’s energy future. The rapid and dramatic improvements in fuel cell technologies have significantly improved their technical and economic viability in a number of areas: electricity to power distributed power systems, utility generation, auxiliary and portable power systems and a variety of vehicle applications from forklifts, specialty vehicles, automobiles and buses.

But what about their use in consumer environments where untrained personnel refuel their own cars? Whereas industry has maintained an excellent safety record in controlled industrial environments, there is little historical experience on which to assess the risk of its use by the general public. For many years, the general public's knowledge of hydrogen has been limited to the Hindenburg disaster in 1937, the Hydrogen Bomb and perhaps the NASA Challenger space shuttle accident in 1986 and many perceive it as dangerous. Of course, none of these examples is an adequate comparison to the new markets for hydrogen and fuel cells, but memories of these events persist. The New York Times, as recently as October 2013, published a feature article in it Sunday magazine titled, "Image of Hydrogen Haunts Hydrogen Technologies" where this reflexive fear of hydrogen was called "The Hindenburg Syndrome." On the brighter side, most experts are aware of the dramatic technical advances and excellent safety record in industry, and are not daunted by the unique properties and hazards posed by hydrogen. In fact several automakers have stated that their future is based on hydrogen fuel cell vehicles.

In support of this transition, there is developing significant ongoing cooperation among the world's safety experts concerning all aspects of using hydrogen in future energy systems. In addition to the International Energy Agency Hydrogen Implementing Agreement Task on Hydrogen Safety (www.ieahia.org), the International Association for Hydrogen Safety (www.hysafe.org) is another notable international effort where experts from government and industry have shared knowledge and experience to assess the risks and identify and resolve knowledge gaps where more information is needed. More information regarding safety handling of hydrogen may be found at their respective web sites. The International Conference on Hydrogen Safety has been held every two years since 2005, and is likewise a good resource for the state of the art and current research directions in hydrogen safety (www.ichs2013.com).

1.4 Scope of the Hydrogen Safety Collaboration

In order to provide a general sense of the breadth and scope of the collaboration, below is a partial list (in no particular order) of some of the topics of shared information:

The Netherlands

The Netherlands shared knowledge gained during their work on THRIVE (Towards a Hydrogen Refueling Infrastructure for Vehicles) which considered customer perspectives towards the availability of fuel cell cars and hydrogen:

- Interdependence of H_2 car sales and H_2 station allocation
- Technical realization and safety
- Environmental impact
- Economic feasibility
- Policy implications

The Netherlands also shared results and data on HyQRA (Hydrogen Quantitative Research Assessment) for the development of a methodology for consistent site risk assessment (collaboration with Italy and Norway).

European Commission

Shared work within the Fuel Cells and Hydrogen Joint Undertaking at the Joint Research Center of the European Commission (JRC) which includes their work on Hydrogen Safety and Storage for Transport as well as the Hydrogen Incidents and Accidents Database (HIAD). Technical activities on which information was shared were high pressure hydrogen storage (GasTeF), Solid-state Hydrogen storage, (SolTeF), on-board safety sensors (SenTeF), and modeling of hydrogen releases (HyMode).

Japan

- The Japan Automotive Research Institute (JARI) shared their experiences with the HySEF (Hydrogen and Fuel Cell Vehicle Evaluations Facility). They have done extensive full scale testing of hydrogen releases and ignition.
- Shared their unpublished information on their analysis of safety related incidents related to their refueling stations, piping and connection failures.
- Mitsubishi Heavy Industries - shared modeling and experimental work on large scale releases. This was used to help validate and calibrate US models

Norway

- Det Norske Veritas (DNV) shared their expertise and work on Quantitative Risk Assessment (QRA) methodologies and their experience with existing European information such as the Norsk Hydro Hydrogen Synergi database.
- Through Gexcon shared their extensive CFD modeling work to help validate the effects of hydrogen releases and ignitions in several scenarios including tunnels, and the effects of trees and other obstructions. SNL ended up purchasing use licenses from GexCon to complement their modeling effort.
- Norway, through the work conducted by Telemark University College, shared valuable experimental data and analysis regarding the consequence of unintended releases and the effects of obstructions.

Greece

Through Democritos, shared their modeling results of hydrogen releases in enclosed equipment rooms.

United Kingdom

Through the Health and Safety Laboratory, shared their early data and testing results on

- auto-ignition of flammable clouds
- vehicle leaks from different locations
- uncontained liquid spills

Italy

Through the University of Pisa shared research information on:

- Experimental results of a test chamber of hydrogen flame propagation studies and effects of doors, windows, barriers, etc.
- Quantitative Risk Assessment of a Gaseous Hydrogen Refueling Station

Canada

Canada shared valuable information on numerous projects:

- Through AVT and Associates, the Hydrogen Venting Project where they validated their models using the HSL experimental data with reference to pipe diameter, wind effects and direction of leaks.
- Through PowerTech in Vancouver, their experimental data on numerous safety events including gunshots, bonfires, rupture and their experiences at the BH Hydrogen refueling station.
- Intelligent Virtual Hydrogen Filling Station
- Hydrogen Clearance Distances
- Quantitative Risk Comparison of Hydrogen and Natural Gas Refuelling Options
- Validation, Calibration and Enhancement of CFD Modeling Capabilities for Simulation of Hydrogen Releases and Dispersion Using Available Experimental Databases – completed in June 2005
- Fuel Cell Oxidant Outlet Hydrogen Sensor Project – completed in June 2006
- Enhancement of Frequency and Probability Analysis, and Consequence Analysis of Key Component Failures of Hydrogen Systems – completed in October 2007.

Germany

- Principles of safety of an experimental set-up ICESAFE
- Transient 2-Phase experiments with N2/LN2
- Scaling of the radiative loads
- Development of a "Toolbox" of Engineering Correlations for simplified risk calculation techniques. The U.S. now has a similar effort.

France

- CEA - Experimental and numerical work on hydrogen releases in small enclosures (garages, etc.)
- Air Liquide – Information on Hydrogen Horizon Experiment (H2E), a 200 million Euro project co-funded by French industry and the French government, experimental R&D results on dispersion, flames and explosions and high pressure storage.

United States

- Experimental and modeling work at Sandia National Laboratories on hydrogen behavior (permeation, buoyant flow, jets, fast fill protocols, model validation), ignition (mechanisms, mixtures, delayed ignition, sustained combustion), hazards (flame radiation, overpressure, oxygen depletion), and consequences (burns, lung damage, shrapnel, and building collapse).

- Through the National Renewable Energy Laboratory (NREL), information developed at their safety sensor testing laboratory was shared on NREL's collaborative efforts with industry to develop and test hydrogen safety sensor technologies.
- First responder training products developed by the Pacific Northwest National Laboratory (PNNL) and partners were shared, including information about Volpentest HAMMER Federal Training Center in Richland, Washington, USA.
- Information and lessons learned from PNNL/DOE safety knowledge tools on safety events and best practices were shared in meeting presentations and related collaborations.

2.0 Task 19 on Hydrogen Safety (2004-2010)

In April 2004, a new task on Hydrogen Safety was proposed at the semi-annual Hydrogen Implementing Agreement Executive Committee meeting in Vienna, Austria. There was interest shown by more than a dozen member countries, and the Committee approved a project definition phase aimed to develop the scope and participation of a three year task. Two project definition meetings were held; one in Washington, DC in June 2004 and a second in Madrid, Spain, in September 2004. A formal annex proposal and work plan were drafted and presented to the Executive Committee in London, UK in October 2004, and the new Task 19 was formally approved for a period of three years.

2.1 Goals and Objectives

The goal of the collaborations on the hydrogen safety task was to address the technical barriers to the widespread commercial use of hydrogen energy among the IEA member countries. The goal of Task 19 was to provide the technical basis for less restrictive and risk informed codes and standards. The approach taken was to develop and conduct:

- Effective risk management techniques
- Testing methodologies, test data, and
- Targeted information products to facilitate the accelerated adoption of hydrogen systems.

2.2 Collaborative Approach

Task 19 was conducted under an approved work plan and conducted within three subtask areas and numerous activities in support of each subtask:

- **Risk Management**: The objective of this subtask was to improve the risk assessment of hydrogen energy systems and focused on quantitative risk analyses (QRA), identification of additional knowledge needed to reduce the uncertainties, and development of testing methodologies around which collaborative testing programs can be conducted.
- **Experimental and Testing**: The objective of this subtask was to share experimental and testing data among participants to minimize the duplication of efforts and to develop

testing methodologies so that shared data could be of benefit to all members. Where knowledge gaps were identified that could be closed through additional experimental or testing efforts, it was hoped that they would be addressed in a coordinated manner in national programs. Work on the effectiveness of various mitigation measures was shared in this subtask.

- **Information Dissemination**: The objective of this subtask was to coordinate the development of targeted information reports, technical papers, and workshops to convey to key stakeholder groups key research and consensus emanating from the collaboration.

The conduct of Task 19 on Hydrogen Safety was achieved through a number of jointly conducted activities:

2.3 Subtask A - Risk Management

The risk management subtask was a collaborative effort dealing with technical issues related to assessing risk related to hydrogen systems and the effectiveness of mitigation measures in achieving an acceptable level of safety.

- Activity A1: Develop uniform risk acceptance criteria and establish links with risk-informed codes and standards.
- Activity A2: Develop a list of appropriate engineering models and modeling tools. Develop simple but realistic physical effects models for all typical accident phenomena (i.e., jet fires, vapor cloud explosions, flash fires, Boiling Liquid Expanding Vapor Explosives (BLEVEs), pool fires, etc.) for education and training, design evaluation and simplified quantitative risk analysis purposes.
- Activity A3: Develop a methodology for consistent site risk assessments.

2.4 Subtask B – Testing and Experimental Program

For almost all risk analysis methodologies, reference data is used for validating modeling and calculations of risk probabilities and/or consequences. With hydrogen being relatively new in large-scale use the question is whether sufficient and validated data exists to perform the required calculations for the risk assessment methodologies identified in Subtask A. Often, implementing these methodologies could identify lacking data which must be assumed making it difficult to draw conclusions related to existing and new regulations (e.g. appropriate safety distances). New applications and equipment have been suggested for hydrogen operating under more extreme conditions than for conventional fuels. The safety of such new applications and equipment should be tested and analyzed. This will also lead to new accidental scenarios addressed by Subtask A.

Subtask B focused on both testing and experimental data, i.e., testing data as collected by checking the performance of applications and equipment and experimental data as collected by experiments with hydrogen release, ignition, fire, explosions and preventive and protective measures. The subtask collaboration was conducted under three activities:

- Activity B1: Survey on existing testing and experimental data

- Activity B2: Survey on ongoing or planned projects
- Activity B3: Analyzing existing data in relation to risk management

To maintain and preserve the results of experimental and testing R&D conducted by participating members, a database was created by the Canada at the University of Trois-Riviere, in Quebec, HyTEX, the Hydrogen Testing and Experimental database. Access to the new database was limited to participants and an approved user list was created. Initial population of the database was initially slow as users were responsible for uploading data and other information to be shared in the collaboration.

2.5 Subtask C - Development of Targeted Information Packages

The development of a homogenous worldwide infrastructure will be necessary before hydrogen energy can achieve widespread utilization and public acceptance. Safety concerns caused by the lack of real operating experience (and the cost of their mitigation) are major inhibitors to the accelerated development of such infrastructure. As information is collected during the testing program, a beneficial impact can only be achieved if it is conveyed to those stakeholders who will participate in the development of the new infrastructure.

The goal of this subtask will be to use the results obtained in the testing and evaluation program to develop targeted information packages for stakeholder groups (permitting officials, insurance providers, system developers, and early adopters of these new products and systems). This activity is more advanced in some countries compared to others that could benefit from the experiences gained in the infrastructure development process.

2.6 Desired Outcomes

As technology advances are realized and more hydrogen components and systems move closer to commercial application, a number of infrastructure issues will move to the forefront. This task will assist the development efforts for new Codes and Standards that will need to be accomplished before the widespread use of hydrogen energy systems is achieved. Likewise, information and data about the risks and hazards introduced by hydrogen energy will help form public perceptions about the safety of such systems. In addition, this data will be useful to insurance providers to establish a basis for insurance rates for the producers and distributors of hydrogen, the manufacturers of early systems, and the purchasers of products that use hydrogen.

There will be a number of key products that would be of significant value in accelerating widespread use of hydrogen. A program of collaboration would facilitate the dissemination of operating information upon which others could base the development of infrastructure in their individual countries.

2.7 Results Achieved in Task 19

Task 19 produced three major reports (available online at www.ieah2safety.com/reports.htm):

2.7.1 Survey of Hydrogen Risk Assessment Methods, 33 pages, January 2008 (PDF)

This report, led by Det Norske Veritas (DNV) of Norway surveyed risk assessment methodologies for hydrogen production, storage and refueling stations. Case studies were completed for 11 projects and the risk assessment methods were compared and evaluated using standard approaches to risk assessment, following representative sets of standards and guidelines. The survey discussed their differences with respect to their applicability in specific systems.

Summary findings of survey

1. The selection and application of risk acceptance criteria for the example studies reflected the general practice for risk assessments, adapted to company guidelines and applicable regulations. No adaptations to the acceptance criteria were made in order to reflect specific technologies or operating procedures of hydrogen facilities. The use of equivalence criteria, for example comparing the risk of using a hydrogen refueling station with a usual petrol station may, in this context, be a good approach.

2. The review showed that specificity with respect to the concept and hydrogen risks in question is as high for the qualitative assessments as for the quantitative assessments.

3. An important development task is to develop a best practice for ignition probability modelling.

4. The assessment of consequences from ignited hydrogen releases uses well established consequence calculation models. These models however, need to be applied correctly in order to reflect the special properties of hydrogen (e.g., lower radiant heat and more prone to explosions/detonations than methane and propane).

5. The importance of existing databases was recognized.

6. State-of-the-art risk analysis within the oil and gas industry is characterized by their ability to reflect the importance of the safety barriers in a technical system, and it is likewise important that risk analyses of hydrogen facilities do the same.

7. Many hydrogen production, storage, and/or refueling stations will have a wide interface between public users and the technical system; for the system to become accepted by the public, it is important that the perceived risk be included in both the risk analysis and risk communications.

8. The case studies focused on technical or operational aspects of safety. The importance of human factors and safety culture in assessing the level of risk was not explicitly considered in the case studies.

2.7.2 Knowledge Gaps White Paper, 54 pages, January 2008 (PDF)

Task 19 experts collaborated to identify and prioritize gaps in hydrogen safety knowledge. Such knowledge gaps included, among other things, failure frequency data, consequence data and identification of hazards required for the conduct of high confidence quantitative risk assessments. The objective of this report was to document discussions and reach consensus on what knowledge gaps existed, their relative priority and how they should be addressed through additional research, testing and modeling activities.

Knowledge gaps were identified in three areas:

1. Existing codes and standards (C&S) as well as gaps relative to on-going C&S development

- Defining Hazardous Zones - This gap relates closely to hydrogen properties and its behavior in confined spaces and outdoors. It has been long suspected by hydrogen experts that, due to hydrogen high buoyancy and diffusivity, recommendations for determining sizes of hazardous zones are likely too conservative and result in inaccurate combustible volumes for hydrogen and higher than necessary hazardous zones. This, in turn, results in higher than necessary use of "classified" components that eventually increase the overall cost hydrogen systems.
- Safety standards for hydrogen fuel cell vehicles - The remaining technical challenges and knowledge gaps mainly reside in: 1) developing a good understanding of the probabilities of encountering component failures that could release hydrogen in unacceptable amounts, 2) the outcomes and probabilities of igniting these volumes in a residential garage, and 3) whether active mitigations of these releases are warranted to arrive at an acceptable risk level and to achieve public acceptance.
- Safety distances for hydrogen fueling stations - The development of separation distances for the new generation on of hydrogen facilities can be determined by SDO's and facility designers in several ways. A conservative approach uses the worst possible accidents in terms of consequences, but such accidents may be such a very low frequency that they would likely never occur. As a result, required distances are generally prohibitive. Risk informed methods of evaluating risk are needed.
- Safety standards for hydrogen detection - Early hydrogen detection is one of the key risk mitigation measures associated with potential hydrogen releases from hydrogen containing equipment and pipework, but the extent of early detection systems required to effectively improve safety and not become an operational nuisance must be determined.

2. Existing risk assessment methods and tools for their application to hydrogen systems

- Establishing acceptable risk criteria - Establishment of risk criteria is a key element in risk management decision making.
- Ignition probabilities – Ignition probabilities of conventional fuels are derived from vast historical data. There is very little data concerning hydrogen ignition of ranges of operating pressure, pipe sizes, and release conditions pertaining to refueling stations.
- Consistent methodology for site specific risk assessments – Although there exists a significant focus on regulations, codes and standards for handling hydrogen risk, the validity of simplified methods is unknown.

3. **Hydrogen behavior and properties, including those related to CFD modeling approaches and tools**

- Ignition – Including spontaneous ignition, ignition probabilities, and disparities in the ignitability of hydrogen-air mixtures
- Effects of protective barriers – The use of protective barriers to reduce clearance or safety distances is not adequately reflected in existing codes and standards. A better understanding is needed concerning the effectiveness of such barriers on the mitigation of risk.
- Consequence modelling – improved consequence models are needed to support a more risk-informed permitting process.
- Wall jets – better understanding of jet releases and the extents of flammable clouds.

2.7.3 Comparative Risk Assessment Studies of Hydrogen and Hydrocarbon Fueling Stations, 86 pages, January 2008 (PDF)

This report is based on the first three years of the Task 19 collaboration during which participating experts presented a number of existing risk assessment studies of refueling facilities. The report had three objectives:

- To describe the available studies in a single document, thus, identifying their key elements - approaches, methodologies, methods of analysis, key results and recommendations, and post-study developments (where available).
- To identify significant findings arising from review and comparison of results to identify additional knowledge gaps.
- Through ongoing revision and updating, to maintain the document as a valuable reference as more studies and research data became available.

Refer to the complete report for more information.

2.7.4 Hydrogen Safety Knowledge Tools

Information exchange and knowledge dissemination were two key aspects of Subtask C work and the following two example accomplishments highlight the importance of specific collaborations in that effort.

- The Hydrogen Safety Best Practices (http://h2bestpractices.org) online manual captures the experience that already exists from industrial, aerospace and laboratory settings for consideration in a wide variety of emerging applications for hydrogen and hydrogen-related technologies. Content is organized into three major sections – Hydrogen Properties, Safety Practices covering management-oriented topics, and Design and Operations covering engineering-oriented topics. Task 19 technical experts and other contributors played a significant role in the design, review and resolution of technical content for the online manual. Another collaboration was also initiated at the joint meeting of Tasks 19 and 22 (Fundamental and Applied Hydrogen Storage Materials Development) held in March 2008 in Sacacomie, Québec. A Task 22 expert team developed new best practices content aimed at scientists and engineers working with reactive metal-hydride hydrogen storage materials. In 2010, the content for "Metal Hydride Storage and Handling" was updated by Sandia National Laboratories to include recommendations for handling larger quantities of these energetic materials.

- Hydrogen Lessons Learned from Incidents and Near-Misses (http://h2tools.org/lessons) is a database-driven lessons learned website which also serves as a voluntary reporting tool for capturing records of events involving either hydrogen or hydrogen-related technologies (e.g., fuel cell vehicles, laboratory facilities, etc.). All identifying information, including names of companies or organizations, locations, and the like, is removed to ensure confidentiality and to encourage the unconstrained future reporting of events as they occur. Information can be self-submitted and anonymity is ensured to encourage contributions and broad use. An initiative was undertaken and completed to augment safety event records previously submitted by the U.S., Canada and Italy with those from other Task 19 member countries: France, Germany, Greece, Japan, Netherlands, Norway, Switzerland and the United Kingdom.

A web site was created to capture the meeting presentation and publish reports: www.ieah2safety.com. This website also contained a "members only" page to facilitate the sharing of unpublished research results among participants. Later, Sandia National Laboratory established a password protected SharePoint site for key documents, meeting materials and to facilitate communications among participating experts.

Under the continued leadership and support of the U.S. and Canada, the task was recognized as an important element in facilitating codes and standards development. Although Task 19 was very productive and considered of great benefit to participants, the original work plan was overly ambitious and could not be completed before the end of the approved task term. As a result, participating experts proposed an additional three-year collaborative effort which was approved in 2010 as Task 31.

3.0 Task 31 on Hydrogen Safety (2010-2013)

Task 31 immediately followed its predecessor Task 19. The new task was again ambitious, but as a result of the previous collaboration, the participating experts had a better idea of what was needed, and developed a very detailed work plan that included over 30 activities under four subtasks. This effort was buoyed by new members such as Germany, Greece and industrial participants such as Air Liquide and United Technologies.

3.1 Goals and Objectives

Since Task 31 on Hydrogen Safety was a continuation of Task 19, the established goals and objectives were similar to Task 19: to address the safety related barriers to the wide spread adoption of hydrogen energy technologies through the development and conduct of effective risk management techniques, testing methodologies, test data, and targeted information products that will facilitate the accelerated adoption of hydrogen systems.

The specific objectives of this task were:

- to develop testing methodologies around which collaborative testing programs can be conducted;
- to collect information on the effects of component or system failures of hydrogen systems; and
- to use the results obtained to develop targeted information packages for selected hydrogen energy stakeholder groups.

Expanded Scope and Activities

Task 31 was a logical progression of Task 19, however there many similarities and some significant changes to the collaboration:

- It continued to address identified knowledge gaps;
- It further developed risk informed acceptance criteria and simplified methodologies;
- It was more focused on real systems;
- It was expanded to stationary systems; and
- It anticipated products that focused on stakeholder groups (approval authorities, insurers, public and system developers)

The work plan developed was again ambitious, but the experts were optimistic that significant results could be achieved. By this time, they had developed a common understanding of the issues and a closer working relationship. The sharing of information was open and the opinions and the consensus developed began to influence national programs. For example, the identification of knowledge gaps guided those who were conducting research and development projects under their respective national programs.

3.2 Approach and Task Structure

The Task 31 work plan was significantly more detailed, comprising four subtasks and 19 activities. Subtask and activities leaders were identified as well as organizations expected to participate in each.

Figure 1 shows the task organization, followed by a description of each subtask and activity**.**

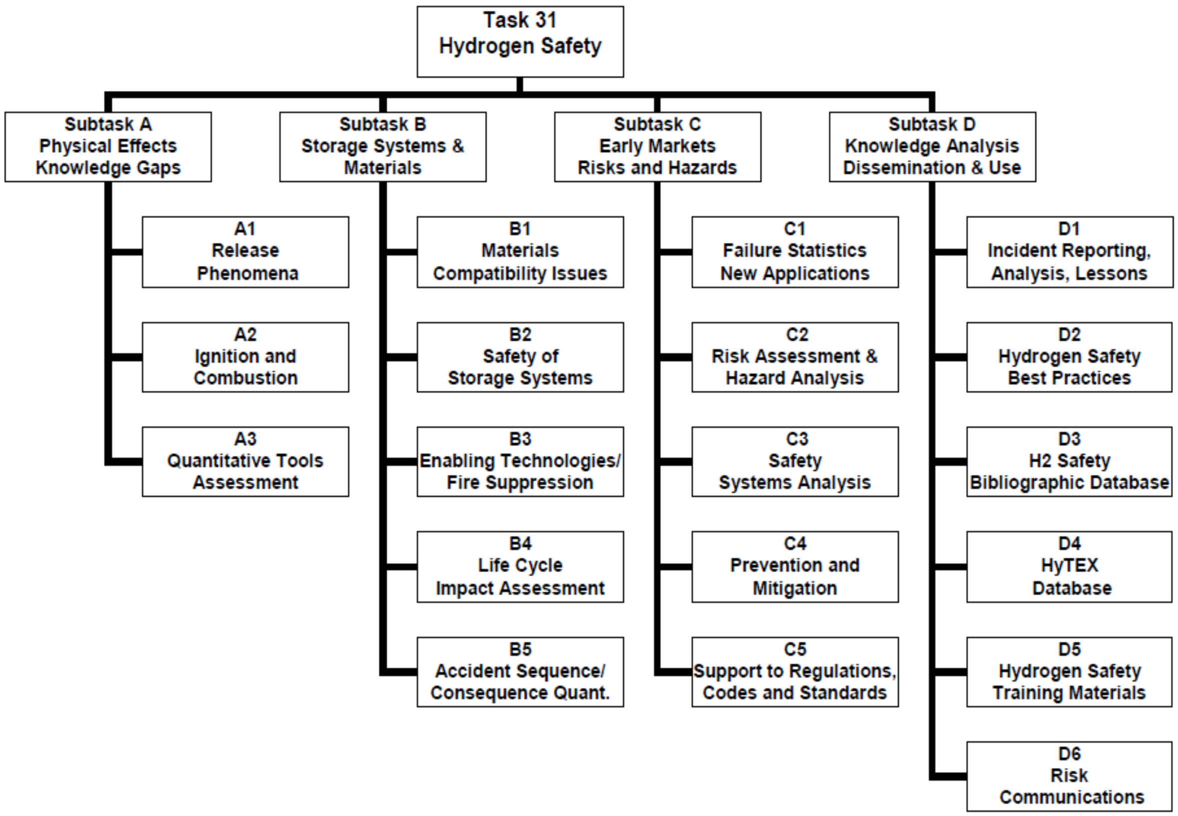

Figure 1 – Task 31 Organization

3.3 Subtask A
Physical Effects Knowledge Gaps

Subtask Leaders:

2010-2012
Pierre Bénard
Professeur/Professor
Département de chimie et de physique/Department of Physics and Chemistry
Institut de recherche sur l'hydrogène/Hydrogen Research Institute
Université du Québec à Trois-Rivières

2012-2013
Daniel E. Dedrick
Manager, Hydrogen and Combustion Technologies
Sandia National Laboratories
dededri@sandia.gov

This subtask addressed knowledge gaps on the physical and chemical properties of hydrogen as a gas or a liquid to increase the knowledge base on hydrogen properties relevant to safety issues. The task was intended to address issues pertaining to sources, release phenomena, dispersion processes, ignition and combustion modes.

Experimental, theoretical and numerical analyses were covered by this task under the following activities.

A.1 Hydrogen release phenomena and behavior of unintended releases (Lead: Thomas Jordan, KIT)

Source characterization and modeling - Examination of issues pertaining to pressure relief devices, the effects of the shape of orifices, and notional approximations to predict behavior (*Participants: University of Ulster, Air Liquide, UQTR, SNL)*

Dispersion behavior – This activity included simulations and experimental studies on the dispersion of hydrogen (post-release and pre-ignition). A number of projects in the following areas were undertaken by participants in support of this activity:

- Enclosed areas and ventilation (simulations, modeling and experiments)
- Large scale gaseous releases (simulations and experiments)
- Obstruction and dispersion
- Release rate issues
- CFD Validation

(Participants: Air Liquide, CEA, JRC, UQTR, HSL, KIT, UNIPI, UU, GexCon, SNL, Demokritos, NREL).

Characterization of surface effects on jet releases. This activity was intended to be a direct continuation of the work of Task 19 and involved the further characterization of the knowledge base on jet releases. *(Participants: UQTR, SNL, UNIPI, AVT, HSL, KIT)*

Gas mixtures: flammability limits, combustion and toxicity. This activity addressed gas mixture issues which impact the use of hydrogen as an energy vector (such as the dispersion properties of hydrogen-natural gas mixtures for fuel use as well as mixtures of hydrogen and other dangerous gases (e.g. CO and ammonia), which are used in the context of quality control of fuel cells. *(Participants: UQTR, PISA)*

Liquid hydrogen release behavior - This activity addressed the behavior of liquid hydrogen releases, including the dispersion behavior of low temperature hydrogen vapor clouds. *(Participants: SNL, HSL, Demokritos, GexCon)*

A.2 Ignition and combustion (Lead: Dag Bjerketvedt, Telemark University)

Ignition of hydrogen releases (issues & modeling) to include ignition mechanisms, ignition probability studies and self-ignition issues *(Participants: SNL, HSL, U. of Ottawa, JARI, KIT).*

Behavior of jet flames, e.g., thermal radiation issues in the presence of a crosswind (experiments and theory) and surface effects on flame jet propagation. *(Participants: AVT, UQTR, HSL, SNL, GexCon, University of Ulster, KIT)*

Effects of overpressure and explosions. *(Participants: Telemark, GexCon, Air Liquide, SNL, KIT, JARI)*

A.3 Assessment of quantitative tools for hydrogen safety (Lead: Pierre Bénard, UQTR)

The objectives of this task were to: (1) establish a recommended set of experimental data for validation of hydrogen CFD simulations, (2) to establish a compendium of existing engineering models including models developed by the HIA Task 19 and (3) propose optimal parameters for models used in CFD simulations. This activity was intended to continue the collaboration and sharing of research information undertaken under the previous Task 19. It, in part, relied on information gained from the activities A1 and A2 and crosses over with several activities of working groups A1 and A2. Its objective is closely linked with those of subtask D (particularly D6). *(Participants: UQTR, others)*

- CFD validation Matrix *(Participants: KIT (lead), SNL, NREL, GexCon, Air Liquide, JRC, CEA, Telemark U.)*
- Engineering correlations *(Participants: UQTR (lead), KIT, SNL)*
- Turbulence modeling issues *(Participants: UQTR. KIT)*

Planned achievements and products

- Experimental characterization of hydrogen releases, ignition, jet fires and explosions.
- Predictive theoretical tools and their validation in the form of CFD models and engineering correlations.
- Reports, white papers, conference presentations and publications in scholarly journals.
- Validation matrix (A3)
- Engineering correlations report (A3)

Subtask A Workshop

A subtask workshop was held at the Holmenkollen Park Hotel, Oslo (Norway), January 9-11, 2012. The objectives of the workshop were: (1) in-depth information sharing, (2) instigation of collaborative activities and examination of upcoming funding opportunities, (3) changes in subtask work items if needed in a context of changing national priorities and (4) improving reporting and communications.

Workshop participants:

Pierre Bénard (HRI/UQTR, Canada)

Dag Bjerketvedt (TUC, Norway)
Rémy Bouet (INÉRIS, France)
Dan Dedrick (SNL, USA)
Andre Gaathaug (TUC, Norway)
Olav Hansen (GexCon, Norway)
Thomas Jordan (KIT, Germany)
Alexei Kotchourkov (KIT, Germany)
Prankul Middha (GexCon, Norway)
Vladimir Molkov (Univ. of Ulster, UK)
Matei Radulescu (Univ. of Ottawa, Canada)
Sidonie Ruban (Air Liquide, France)
Knut Vågsæther (TUC, Norway)
Steven Weiner (PNNL, USA)

Proceedings of the workshop

To facilitate discussion during the workshop, an overview of several national programs was presented by the workshop participants. The following lists the Subtask A technical topics presented:

1. Thomas Jordan of KIT, (Germany) presented a detailed review of the R&D activities KIT was conducting on hydrogen safety, referencing the subtask work items:

- R&D activities on non-reactive flows including:
  - studies of cryojets, cryofilling, destructive testing of pressurized vessels (including bonfire)
  - evaporation of LH2 releases (addressing work items A1.1, A1.2 and A1.5 of Subtask A).
  - The HyCube test facility
  - Safety analyses of LH_2 pipelines
  - Hydrogen storage in caverns
  - methane reforming in liquid metals
  - materials compatibility study of a natural gas system for hythane.

- R&D activities performed at KIT on reactive flows including:
  - ignition and auto-ignition of high pressure inventories
  - unconfined explosions as well as vented explosions experiments
  - "tunnel roof" explosions studies
  - large scale vertical gradient combustion simulations and experiments
  - reactivity of hydrogen at elevated temperature and subatmospheric pressures (including jet ignition studies)
  - flame stability in curvilinear pipes (ongoing projects).

2. Alexei Kotchourko, also from KIT:

- Results of a completed IA-Hysafe standard benchmark exercise (SBEP) based on experimental data from a simulated release in a garage by CEA.

- Validation of engineering correlations for hydrogen (which is a work item of workgroup A.3). He reported that a web site was being set up at KIT that could be used as a web interface for a physical effect calculator. This activity would be considered as the final form of the task 31 work product on engineering correlations (Subtask A.3). Pierre Bénard and his group participated in this activity for thermal radiation modeling and flammable extent estimations.

3. Dan Dedrick (Sandia National Laboratories)

   - Scientific approach to risk analysis in which R&D needs for code development was identified (knowledge gaps), the required R&D is prioritized and performed, and the knowledge gained is integrated into codes and standards.
   - Model for quantitative risk assessment of indoor refuelling. Sandia is interested in developing engineering tools that can properly be used to predict hydrogen safety issues.

4. André Gaathaug (Telemark University College)

   - Results from a numerical and experimental study of DDT behind a single obstacle. The simulations were performed by an in-house code (FLIC). The experiments were performed in an open-ended rectangular explosion chamber filled with premixed hydrogen (concentrations ranging from 15 to 40% by volume). Ignition occurred at the closed end of the chamber. Enhanced numerical Schlieren images of the shock wave structures were presented.

5. Dag Bjerketvedt (Telemark University College)

   - Overview of the R&D activities performed at his institution on hydrogen safety and related activities. The following areas were covered:
     - Flame acceleration in an obstructed channel (rectangular section)
     - FLACS simulations of the Porsgrunn incident of 1985
     - Hydrogen explosions in soap bubbles
     - Explosions of liquid CO2 storage units
     - CO_2 BLEVE incidents and CO_2 vessel explosions experiments through tank ruptures induced by a gun shot.

6. Sidonie Ruban (Air Liquide) presented the R&D activities at Air Liquide in hydrogen safety

   - Leak & dispersion
   - Flame & explosions and storage safety
   - A short presentation of the new HyIndoor project was also given.

7. Olav Hansen

   - Development of FLACS, which arose in parallel with the development of the oil industry in Norway in order to address safety issues of interest to the industry
   - Review of recent improvements, current issues and suggested fixes to the software package, followed by a discussion of the role of computational fluid dynamics software packages in quantitative risk assessments.

8. Prankul Middha (Gexcon)

- Fire modeling (implementing of new functionality in FLACS to simulate jet fires and flares)
- Liquid hydrogen spill modeling (taking into account condensation of air and water and multiphase flow issues)
- Hazard classification of hydrogen releases using the Equivalent Stoichiometric Cloud (ESC) put forward by GexCon
- The ongoing benchmarking exercises (part of the IA-HySafe initiative) and initial results from GexCon were presented, based on experimental data from FM Global in a 64 cubic meter explosion test chamber involving several gases including hydrogen, methane and propane.

9. Matei Radulescu then discussed ongoing R&D activities
   - Self-ignition of high pressure hydrogen jets for H2Can research network in Canada
   - Dynamics of pressure jets and a model for self-ignition
   - Model predictions for the ignition limits of both unconfined and confined releases were compared with experimental data
   - Criteria for self-ignition
10. Vladimir Molkov presented a novel correlation in terms of the Reynolds, Mach and Froude numbers for hydrogen flame lengths that matches the available experimental data up to 90 MPa for nozzle diameters ranging from 0.4 to 51.7 mm. This result closes a longstanding knowledge gap for hydrogen flames. Professor Molkov also restated his opinion that the issue of the safety of the design of pressure relief devices for pressurized storage tanks used in vehicular applications should be carefully examined.
11. Rémy Bouet (INERIS)
   - R&D activities on hydrogen explosion and dispersion at INERIS
   - Leakage and formation of flammable atmospheres in confined spaces
   - Explosions and fires of hydrogen and hydrogen mixtures
   - Bursting of pressurized storage units
   - Codes and standards and adaptations of regulations relative to experiments on hydrogen jet explosions and vented explosions were discussed.
12. Knut Vågsæther (Telemark University College)
   - Modeling of flame acceleration of hydrogen-air mixtures
   - Deflagration to detonation transition of hydrogen/methane mixtures in a 6 meter explosion tube with an internal diameter of 14 cm, in the presence of a succession of annular obstacles with blockage ratios ranging from 0.4 to 0.7. Simulation results were compared with experimental data.
13. Pierre Bénard (Hydrogen Research Institute,University of Trois Riviere, Quebec, Canada) reviewed research on surface jets and hydrogen-carbon monoxide mixtures.

Finally, Thomas Jordan discussed the new H2FC European infrastructure project. This project offers free access to the experimental facilities to support R&D activities in Fuel Cells and Hydrogen technologies.

Planned Subtask A Products

A fundamental activity of Subtask A was the closure of knowledge gaps. Work group products were joint projects (generally non-funded) that addressed specific knowledge gaps of the hydrogen community, and these were part of work group A.3. Two work products were identified:

1. **Validation matrix for computer fluid dynamics** codes for the purpose of hydrogen safety studies (Validation Matrix). The objective is to provide guidance on the validation of various computer fluid dynamics software used in safety analysis of hydrogen systems and facilities.
2. **Engineering correlations** to describe physical effects relevant to hydrogen safety issues. This activity addressed the uncertainties concerning the validity of engineering correlations commonly used for hydrogen safety analysis. It was expected that this work product would take the form of a web application that could eventually be made publicly available.

The participants agreed that a formal process should be implemented to declare a knowledge gap closed, and that it would be preferable that this process be the same for all subtasks of Task 31.

3.4 Subtask B
Hydrogen Storage Systems and Materials Compatibility

This section was submitted by Subtask (B) Technical Leader: Y. F. Khalil

Subtask Leader:
Y. (John) Khalil, Ph.D., Sc.D.
Principal Research Engineer and Project Leader
Physical Sciences Department
United Technologies Research Center (UTRC)

Executive Summary

Subtask-B (*Hydrogen Storage Systems and Materials Compatibility*) of Task 31 "*Hydrogen Safety*" of the International Energy Agency/ Hydrogen Implementation Agreement (IEA/HIA) has five (plus 2 new focus areas) focus areas and specific work products as follows:

- **B1:** Hydrogen storage materials reactivity, safety, and toxicity.
- **B2:** Hydrogen storage systems: on-board reversible systems and off-board regenerable systems for light-duty vehicles. The activities of this focus area include system-level qualitative and quantitative risk analysis (FMEA, HAZOP, and accident sequence development through fault tree/event tree linking).
- **B3:** Computational fluid dynamics (CFD) simulations of subsystems (e.g., fast filling of hydrogen tanks). This focus area also includes the associated experimental investigations.
- **B4:** Hydrogen fire suppression systems for mobile and stationary applications. Examples of mobile applications include man-portable power systems (integrated H2 storage and delivery subsystem with PEM fuel cell stack), forklifts, unmanned aerial systems (UAS), and unmanned underwater vehicles (UUVs). Examples of the stationary applications include fuel cell stacks/ auxiliary power systems (APS), hydrogen refueling stations.
- **B5:** Life cycle impact analysis (LCIA) of hydrogen storage materials and systems (cradle-to-cradle, fate of spent fuel/storage media at end of life, potential for recycling/regeneration, etc.).

In addition to these five focus areas, two new focus areas are added (*as discussed during Task 31 Hydrogen Safety Experts meeting in Buxton, UK, April 10-12, 2013*). These are as follows:

- **B6:** Hydrogen storage systems for unmanned aerial vehicles (UAV), unmanned underwater vehicles (UUV), robotics, and forklifts. Figure 2 (*vide infra*) show these activities that utilize hydrogen storage to power the proton exchange membrane (PEM) fuel cells.

(A) Unmanned aerial vehicles (UAV).

(B) Unmanned underwater vehicles (UUV).

(C) Forklifts.

Figure 2 – Hydrogen storage for mobile applications: UAVs, UUVs, and forklifts.

- **B7:** Safety of hydrogen generation from nuclear, biomass, wind turbines integrated with water electrolyzers, and waste water treatment.
  - Advanced nuclear reactors + water-splitting chemical cycles → hydrogen + oxygen
  - Water splitting to produce H_2 using direct thermal energy from nuclear or concentrated solar power (CSP).
  - Biomass → gasification → Syngas ($CO + H_2$) → separation → hydrogen.
  - Wind turbines + water electrolyzer → $H_2 + O_2$
  - Sludge from waste water treatment → fermentation → CH_4 → reforming with steam → hydrogen.

Table 1 of this report summarizes the presentations made by Subtask B members during the following Task 31 Hydrogen Safety Experts meetings:

- Instituto Superiore Anticendi, Rome, Italy, October 4-6, 2010.
- Hyatt Fisherman's Warf, San Francisco, CA, USA, September 15, 2011
- Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, April 11-13, 2011
- IEA/HIA offices, Bethesda, MD, October 4-5, 2012
- L'Air Liquide, 75 Quai D'Orsay 75007 Paris, France, April 2012
- Hydrogen Safety Laboratory (HSL), Buxton, UK, April 10-12, 2013

Table 1 – Summary of Subtask B papers presented during Task 31 Hydrogen Safety Experts Meetings.

Task 31 Meeting Location and Date	**Presentation Title**	**Presenter and Presentation Highlights**
Instituto Superiore Anticendi, Rome, Italy October 4-6, 2010	1) Analysis of selected failure mechanisms of on-board vehicle hydrogen storage systems.	Presenter: Dr. John Khalil, UTRC Highlights: John discussed his fault tree (FT) models for selected failure mechanisms of on-board hydrogen storage in solid-based (metal and chemical hydrides) systems. Also, he discussed hydrogen permeation / leakage from storage vessels and runaway thermal decomposition

Task 31 Meeting Location and Date	Presentation Title	Presenter and Presentation Highlights
		(thermolysis) reaction in a chemical hydride based storage system.
	2) Use of hydrogen – current application, issues and future developments.	Presenter: Dr. Mark Royle, HSL (Health & Safety Laboratory, www.hsl.gov.uk) Highlights: Mark discussed the use of hydrogen in different applications, safety issues associated with hydrogen use, and future developments of the hydrogen technologies.
Hyatt Fisherman's Wharf, San Francisco, CA, USA. September 15, 2011	1) Hydrogen safety and storage materials reactivity for on-board vehicular applications.	Presenter: Dr. John Khalil, UTRC Highlights: John discussed the scope and tasks of his DOE contract on hydrogen storage materials reactivity and safety for on-board systems in light-duty vehicles.
	2) Hydrogen Storage Engineering Center of excellence (HSECoE).	Presenter: Dr. John Khalil, UTRC Highlights: John gave a high-level overview of activities of the DOE HSECoE program as follows: a) Phase-I (hydrogen storage materials identification and screening) has been completed, b) Phase-II of HSECoE will focus on adsorbents (AX-21 and MOF materials) and liquid-phase chemical hydrogen storage materials and systems, c) No future research work will be pursued in the reversible metal hydrides or solid chemical hydrides. To date, reversible metal hydrides cannot meet all DOE targets simultaneously, and d) UTRC is currently developing a safety testing plan for cryosorption hydrogen storage tanks.
	3) Hydrogen fuel-cell forklifts. .	Presenter: Dr. Bill Houf, SNL Highlights: SNL completed additional simulations on releases from H_2 fuel-cell forklifts in enclosed spaces. Different leak sizes have been examined. Also, SNL continued experiments on

Task 31 Meeting Location and Date	Presentation Title	Presenter and Presentation Highlights
		measuring concentrations, flammability factors, and light-up boundaries for laboratory-scale H_2 jet releases.
	4) NFPA-2 and HIPOC H_2 codes and standards.	Presenter: Dr. Bill Houf, SNL Highlights: Bill discussed SNL activities with NFPA. In this respect, SNL continues to work with NFPA-2 and HIPOC H_2 codes and standards groups.
Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany. April 11-13, 2011	1) Hydrogen Storage Materials Safety and Screening Criteria.	Presenter: Dr. John Khalil, UTRC Highlights: John presented a new framework for safety categorization of hydrogen storage media. The storage media could be solid, liquid, or slurry and include: metal hydrides, chemical hydrides and adsorbents. Categorization is based on risk assessment of: material reactivity, pyrophoricity, sensitivity to mechanical impact, toxicity, chemical stability, ability to cause runaway chemical reaction, on-board vehicular use & handling and off-board regeneration/recycling. Material risk includes: adverse impact on human safety, health and environment impact. Four categories of material risk: Green, Yellow, Orange and Red.
	2) Chemical Sensor Array Based Early Fire Warning System.	Presenter: Dr. Bill Buttner, PNNL. Highlights: Bill discussed the use of chemical sensor array for early warning systems.
	3) JRC activities on fast filling of hydrogen tanks.	Presenter: Dr. Daniele Baraldi, JSC. Highlights: Dr. Baraldi discussed his experiments and CFD simulations of fast filling of hydrogen storage tanks.
	4) High pressure full composite cylinder safety: Hydrogen cylinder behavior in fire.	Presenter: Ms. Sidonie Ruban, Air Liquide, France. Highlights: Ms. Ruban discussed her experimental program to characterize the behavior of

Task 31 Meeting Location and Date	Presentation Title	Presenter and Presentation Highlights
		hydrogen composite cylinder under fire conditions.
	5) Risk Mitigation Experiments for Selected Solid-State Hydrogen Storage Media.	Presenter: Dr. John Khalil, UTRC Highlights: John discussed the high-level objectives of his research program with the U.S. Department of Energy. The research objectives focused on: a) Contribute to quantifying the U.S. Department of Energy (DOE) on-board storage safety target: "*Meets or exceeds applicable standards*", 2) Evaluate reactivity of key materials under development in the materials Centers of Excellence, 3) Develop methods to reduce risks.
IEA/HIA offices, Bethesda, MD. October 4-5, 2012	Framework for Maxsorb AX-21 Safety Testing.	Presenter: Dr. John Khalil, UTRC Highlights: Dr. Khalil applied Taguchi's mixed-levels design of experiments methodology to analyze the dust cloud deflagration results for Maxsorb AX-21 in a mixture of hydrogen and air. The $(dP/dt)_{MAX}$ response surface was determined as a function of the dust concentration and H_2 mole fraction in the air.
Air Liquide, 75 Quai D'Orsay 75007 Paris, France, April 2012	1) Incidents Involving Cryogenic Gas Purifiers: Lessons Learned and Risk Mitigation Methods.	Presenter: Dr. John Khalil, UTRC Highlights: EIGA-reported industrial and laboratory incidents involving cryogenic gas purifiers. This presentation describes the incidents, their root causes, consequences, and risk mitigation methods. Source: *European Industrial gases Association (EIGA) Report no. IGC Doc 43/07/E, 2007.*
	2) An overview of hydrogen storage materials and systems development.	Presenter: Dr. John Khalil, UTRC. Highlights: John gave a status update on HSECoE Phases I & II: development of hydrogen storage materials and systems: Liquid

Task 31 Meeting Location and Date	Presentation Title	Presenter and Presentation Highlights
		chemical hydrides materials and systems development. He discussed solid ammonia borane (AB) / silicon oil slurry (PNNL & UTRC), solid AB / ionic liquids (LANL & UTRC). He also discussed the cryoadsorption of LH2 on Maxsorb activated carbon or MOF-5 (JPL, UQ, UTRC, and BASF). Finally, Dr. Khalil presented the path forward for hydrogen storage materials and systems (HSECoE Phase-II).
	3) CFD simulations of fast filling of hydrogen tanks.	Presenter: Dr. Daniele Baraldi, JSC. Highlights: Dr. Baraldi discussed his work on computational fluid dynamics (CFD) simulations of fast filling of hydrogen storage tanks.
Hydrogen Safety Laboratory (HSL), Buxton, UK. April 10-12, 2013	1) Safety Tests of Hydrogen Storage Material Discovery for Light-Duty Vehicles (LDV).	Presenter: Dr. John Khalil, UTRC. Highlights: John presented his safety tests for *cryoadsorbents* as hydrogen storage materials. He discussed the following topics: ▪ *Maxsorb AX-21: activated carbon (AC) for H2 storage.* ▪ *Dust cloud explosion of AC/Air vs. AC/H_2/Air hybrid mixtures*.

Subtask (B) Participating Organizations

- United Technologies Research Center (UTRC), USA.
- Air Liquide, France.
- Japan Automobile Research Institute (JARI), Japan.
- Université du Québec à Trois-Rivières (UQTR), Canada.
- European Commission Joint Research Center (JRC), NL.
- Ulster University, UK.
- Karlsruhe Institute of Technology (KIT), Germany.
- Gexcon, Norway.
- Toho University, Japan.
- TNO, NL.
- Sandia National Laboratories (SNL), USA.

Subtask B: Publications and Presentations

Recent publications:

1. Khalil, Y. F. (2013). Experimental determination of dust cloud deflagration parameters of selected hydrogen storage materials: Complex metal hydrides, chemical hydrides, and adsorbents. *Journal of Loss Prevention in the Process Industries*, 26 (1), 96–103.

2. Khalil, Y. F., et al. (2013). Experimental and theoretical investigations for mitigating NaAlH4 reactivity risks during postulated accident scenarios involving exposure to air or water. *Journal of Process Safety and Environmental Protection*, 91 (6), 463-475.

3. Khalil, Y. F. (2013). Experimental investigation of the complex deflagration phenomena of hybrid mixtures of activated carbon dust/hydrogen/air. *Journal of Loss Prevention in the Process Industries*, 26 (6), 1027-1038.

4. Khalil, Y. F. (2011). Reciprocity of safety insights between risk analysis and codes and standards of vehicular hydrogen storage. *Proceedings of Risk Management, American Nuclear Society (ANS)* publisher, La Grange Park, IL, 277-283.

Recent presentations:

1. Khalil, Y. F., “Reciprocity of Safety Insights between Risk Analysis and Codes and Standards of Vehicular Hydrogen Storage,” Proceedings of Risk Management, ANS, ISBN: 978-0-89449-074-4, pp.277-283, 2011.

2. Khalil, Y. F., “Ammonia Borane Dust Cloud Combustion Characterization,” presentation at the DOE Hydrogen Storage Engineering Center of Excellence, Santa Fe, NM, October 10-14, 2011.

3. Khalil, Y. F., et al., “Quantifying and Addressing the DOE Material Reactivity Requirements with Analysis and Testing of Hydrogen Storage Materials and Systems,” DOE Hydrogen Program, Annual Merit Review (AMR) and Peer Evaluation Arlington, VA, May 9-13, 2011.

4. Khalil, Y. F., “Risk Mitigation Tests for Selected Hydrogen Storage Solid-State Media,” The International Energy Agency (IEA), Task 31 (Hydrogen Safety) meeting, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, 2011.

5. Khalil, Y. F., et al., “Potential Diffusion-Based Failure Modes of Hydrogen Storage Vessels for On-Board vehicular Use,” Manuscript in preparation for the Proceedings of the AIChE Conference, Hydrogen Storage System Engineering and Applications – Risk Reduction Session, Salt Lake City, UT, November 7-12, 2010.

6. Khalil, Y. F., “Selected Risk Mitigation Tests and Failure Mechanisms of On-Board Vehicle Hydrogen Storage Systems,” Invited Presentation, Hydrogen Safety Task 19, International Energy Agency, Rome, Italy, October 4-6, 2010.

7. Khalil, Y. F. and M. Modarres, “Safety Importance Measures for a Conceptual Baseline Design of an On-Board Reversible Hydrogen Storage System,” Proceedings of the First International Conference on Materials for Energy, UTRC/University of Maryland Joint Paper # 1368, DECHEMA e.V., Karlsruhe, Germany, July 4-8, 2010.

8. Khalil, Y. F., D. Mosher, J. Cortes-Concepcion, C. James, J. Gray and D. Anton, “Adverse Reactivity Effects and Risk Mitigation Methods for Candidate Hydrogen Storage Materials,” Proceedings of the First International Conference on Materials for Energy, UTRC/SRNL Joint Paper # 1369, DECHEMA e.V., Karlsruhe, Germany, July 4-8, 2010.

Submitted by Subtask (B) Technical Leader:

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3.5 Subtask C
Early Markets: Risk Characterization and Hazard Analysis

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In order to provide a more near term relevance for the task, Subtask C was initiated to provide stakeholders with needed support and data to facilitate early commercialization activities. Early market applications for new hydrogen technologies for mobility, stationary and materials handling applications will result in significant involvement of consumers. This will require adjustment to traditional approaches to risk characterization and hazard analysis that focused on operator and worker safety to a focus on the general public. Safety assessment methods, data, and use of prevention and mitigation features need to be tailored to address these early applications, e.g., hydrogen forklifts/materials handling facilities, car and bus fleets, stationary power units, etc. For these systems, efforts were made to systematically collect failure and leak frequency data, and other information to assess their safety and facilitate their commercial introduction.

Since new technologies are penetrating densely populated urban environments, the intended focus was placed on risk mitigation technologies and methods such as sensors, barriers/walls and safety distances. The results of these efforts are aimed at codes and standards developers to ensure that they are risk-informed and evidence-based.

There were a number of collaborative activities under this subtask:

1. **Failure (frequency) statistics of new hydrogen applications.** This activity targets emerging hydrogen markets. This effort focused is on hydrogen forklift operations in US and Canada, specifically the information already collected by NREL. Collected data was used in Bayesian statistical analysis to derive credible correlations for the use in quantitative risk assessment.
2. **Improvements in risk assessment and hazard analysis methodologies.** The scope included monitoring and proposing further developments in risk assessment methodologies. The intent is to review related publicly available risk assessment studies, specifically QRAs and identify improved methods to address known weaknesses in existing risk assessment activities. Ultimately, it would be desirable to establish an international standard for performing QRAs of hydrogen facilities.
3. **Systems safety analysis of hydrogen applications.** The scope included both qualitative and quantitative risk assessments of real world hydrogen systems and equipment with a purpose of establishing their suitability for intended operation (i.e. strengths and weaknesses in design) and identifying potential gaps in existing RCS pertaining to those applications.
4. **Prevention and mitigation.** The scope included evaluation of the following prevention and mitigation measures: a) sensors; b) barriers / walls; c) safety distances based on

Subtasks A and B contributions; d) visual inspection, testing and maintenance schedules; e) safety education and training. Progress on several new and novel sensor approaches were shared in the collaboration.

- **UQTR (University of Quebec a Trois-Rivieres)** studied the applications and the market potential of sensors based on MEMS technology.
- **The U.S. National Renewable Energy Laboratory (NREL)** shared information on:
  - The impact of environmental parameters (T, P, RH, [H2])
  - Robustness to chemical interferents
  - Control parameters (operating T, signal management)
  - Comparative studies with thermal conductivity and catalytic sensors
- **JRC-IET (Joint Research Center – Institute of Energy and Transport)** measured:
  - response times
  - recovery times
  - effects of gas flow on final sensor response
- **Element One, Inc. (U.S**.) shared information on novel, very low-cost chemochromic and wireless sensors for leak detection.

5. **RCS development support (knowledge analysis and recommendations) to relevant ISO and IEC standard development activities.** The scope included provision of risk-informed and evidence-based information and participation in the relevant ISO and IEC technical committees and working groups. Activity leader: TBD

3.6 Subtask D
Knowledge Analysis, Dissemination and Use

This section was submitted by Subtask (D) Technical Leader: Steven C. Weiner

Subtask Leader:
Steven C. Weiner
Pacific Northwest National Laboratory
USA

Safety knowledge tools can take many forms and serve to help disseminate the wealth of information and data that already exists on the safe use and handling of hydrogen and to remove barriers to the successful commercialization of hydrogen and fuel cell technologies. As worldwide interest and attention grows in expanded applications of hydrogen and hydrogen systems, such knowledge needs to be shared more broadly.

The work of the subtask extended the work previously conducted under Task 19 Subtask C, Targeted Information Packages for Stakeholder Groups, whose accomplishments were well captured in a task white paper.[1] Through continued collaborations, enhancements to hydrogen safety knowledge databases and websites have been integral to the work of Subtask D and the member countries. Progress is captured in the project summaries that follow in Appendices I-III.

Information and knowledge dissemination from across the entirety of Task 31 has also been a key aspect of the contribution and responsibility of Subtask D. Case studies, technical reports and presentations/publications have often resulted from the collaborative efforts of Task 31 and its predecessor, Task 19. However, technology information and knowledge exchange among participating hydrogen safety experts can happen in many different ways while serving the objectives intended by the IEA HIA as well as the objectives of national programs whose experts are represented.

Under the leadership of Subtask D, a task white paper was prepared and presented at the International Conference on Hydrogen Safety, illustrating through specific examples how value is created by these collaborations.[2] Those examples emphasize how such work is addressing hydrogen safety-related barriers to facilitate the implementation and utilization of hydrogen and hydrogen-related systems. As of the completion of this final report, the paper is available on the IEA HIA website (http://ieahia.org/new.htm) and has been selected, pending editorial review, for publication in a special issue of the International Journal of Hydrogen Energy.

[1] Weiner, S.C. and Blake, C.W., "Safety Knowledge Tools Enhanced by International Collaboration," A white Paper of the International Energy Agency Hydrogen Implementing Agreement Task 19 – Hydrogen Safety, PNNL-19901, October 18, 2010.
[2] Weiner, S.C., "Advancing the Hydrogen Safety Knowledge Base," PNNL-SA-91531, International Conference on Hydrogen Safety, Brussels, Belgium, September 9, 2013.

We can conclude from Subtask D initiatives as well as those of Task 31 as a whole that collaboration, information exchange and knowledge building can occur in many different ways. We should be encouraged to build on these successes by continuing to address high priority safety knowledge barriers via mechanisms that support collaborations of many types.

Submitted by:

Steven C. Weiner
Pacific Northwest National Laboratory
Subtask Leader, Subtask D

3.7 Results Achieved in Task 31

As in the previous task, there was great benefit to the information exchange between participants and ongoing coordination of complementary research and development activities within each domestic program. This information exchange greatly reduced the duplication of efforts.

As part of the increased attention to producing products of value to stakeholders, the task created a new project to conduct two stakeholder workshops, one in North America and another in Europe. After some delays due to obtaining the necessary sponsorship, an invitation-only North America Hydrogen Safety Workshop was held in Bethesda, Maryland, USA in October 2012. A second workshop was to be held in Europe in 2013, but that workshop was put on hold. More information on the Bethesda workshop may be found at www.ieah2safety.com/workshop/.

After a strong start, the task encountered severe difficulties when Canada, who was sharing support of the task management with the U.S., withdrew from all IEA hydrogen activities in April 2012 due to a shift in national policy. In 2013 the U.S. withdrew its support of the task management and curtailed attendance by U.S. experts at task meetings. Without participation by two major participants and without funded task management, task progress deteriorated.

4.0 Conclusions

There was significant benefit derived by participating members from the two collaborations in hydrogen safety. The regular in-person meetings by the hydrogen safety community resulted in better coordinated national research programs and an increased consensus on many of the technical issues of hydrogen safety. However most experts believe that much more can be accomplished as hydrogen and fuel cells are moving into the energy arena.

A new hydrogen safety collaboration is currently in the planning phase and will be proposed to the Executive Committee of the IEA Hydrogen Implementing Agreement in late 2014 or early 2015.

APPENDIX - Task 31 Project Summaries

Below is a list of project summaries received from task participants summarizing fifteen collaborative efforts undertaken within the task and a bookmark to each project.

Project title	Page
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Energy Technologies Institute (ETI) High Hydrogen Project	55
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Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title**: Risk Reduction Potential of Accident Prevention and Mitigation Features.

II. **Project Start/Finish Dates:** May 2010 to July 2011.

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** 0.3 person-yrs.

IV. **Project Leader, Principal Investigator(s), and Country:** Jeffrey LaChance, Sandia National Laboratories (USA).

V. **Task 31 Work Plan Subtask or Activity Supported**: Subtask C - Early markets: risk identification and hazard analysis; Prevention and Mitigation and RCS Development and Support

VI. **Summary:** Quantitative Risk Assessment (QRA) can help to establish a set of design and operational requirements in hydrogen codes and standards that will ensure safe operation of hydrogen facilities. By analyzing a complete set of possible accidents in a QRA, the risk drivers for these facilities can be identified. Accident prevention and mitigation features can then be analyzed to determine which are the most effective in addressing these risk drivers and thus reduce the risk from possible accidents. This work presented some preliminary QRA results where the risk reduction potential for several active and passive mitigation features was evaluated. These measures include automatic leak detection and isolation systems, the use of flow limiting orifices, and the use of barriers. Reducing the number of risk-significant components in a system was also evaluated as an accident prevention method. In addition, the potential reduction in separation distances if such measures were incorporated at a facility was also determined.

VII. **Collaborations:** There was no collaboration on this work with other Task 31 participants.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** Generation of risk-informed hydrogen codes and standards.

IX. **Project Narrative:** A concept being pursued in the National Fire Protection Association (NFPA) hydrogen standard development is to take credit for prevention and mitigation features as a means to reduce the separation distances. The reduction in the separation distance could be expressed as a reduction factor that represents the ratio of the separation distance without any mitigation feature to the separation distance with a mitigation feature credited. This project provided preliminary results of the quantitative risk assessment (QRA) for the following mitigation features taken individually (the risk reduction of combinations of these features has currently not been performed):

- Automatic leak detection and isolation
- Use of flow limiting orifices
- Use of barriers
- Reduction in the number of components

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities: With the exception of the use of barriers, the results from this work have not been incorporated into NFPA C&Ss. Uncertainty remains with respect to leak detection reliability. Work to improve the understanding and reliability of leak detection methods would be an excellent area for collaboration.

XI. Acknowledgements: This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen, Fuel Cells and Infrastructure Technologies Program under the Codes and Standards subprogram element managed by Antonio Ruiz.

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. Project Title: Risk Comparison of NFPA and ISO Approaches for Evaluating Separation Distances.

II. Project Start/Finish Dates: January 2010 to January 2012.

III. Estimated Level of Effort of Work Contributed to Task 31 Collaboration: 0.6 person-yrs.

IV. Project Leader, Principal Investigator(s), and Country: Jeffrey LaChance, Katrina Groth, and Bobby Middleton, Sandia National Laboratories (USA).

V. Task 31 Work Plan Subtask or Activity Supported: Subtask C - Early markets: risk identification and hazard analysis; RCS Development and Support

VI. Summary: The development of a set of safety codes and standards for hydrogen facilities is necessary to ensure they are designed and operated safely. To help ensure that a hydrogen facility meets an acceptable level of risk, code and standard development organizations (SDOs) are utilizing risk-informed concepts in developing hydrogen codes and standards. Two SDOs, the National Fire Protection Association (NFPA) and the International Standardization Organization (ISO) have been developing standards for gaseous hydrogen facilities. Sandia National Laboratories (SNL) supported efforts by both of these SDOs to develop the separation distances included in their respective standards. Important goals in these efforts are to use a defensible, science-based approach to establish these requirements and to the extent possible, harmonize the requirements. International harmonization of regulations, codes and standards is critical for enabling global market penetration of hydrogen and fuel cell technologies.

VII. Collaborations: Task 31 participants from other countries (France and Canada) supported the ISO separation distance work.

VIII. Specific Technical Challenges or Barrier Being Addressed: Generation of risk-informed hydrogen codes and standards.

IX. Project Narrative: The successful approach to risk-inform the separation distances in the NFPA standards is a model for establishment of additional requirements by NFPA and other SDOs. In fact, ISO adopted nearly the same approach to determine the separation distances in ISO 20100, "Gaseous hydrogen – Fuelling stations". In addition, the data and consequence models used in the NFPA analysis have also been generally adopted for use in the ISO separation distance evaluation. However, there are some important differences in the ISO and NFPA analyses that make it difficult to compare the resulting separation distances. These differences include the scope of the application (i.e., bulk storage versus fueling station), the differences in the separation distance table format used in the specific standards (pressure ranges and exposures), the risk acceptance criteria used in the risk analysis, the utilization of component leak data in the risk assessment, and the importance placed on the risk results. This project identified the differences between the approaches and data utilized in NFPA and ISO assessments and their effect on the resulting separation distances.

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities: ISO 20100, "Gaseous hydrogen – Fuelling stations" was rejected. Efforts are currently underway to generate a new standard. There is an opportunity for international collaboration on this standard with a goal of harmonization with the NFPA 2 standard used in the USA.

XI. Acknowledgements: This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen, Fuel Cells and Infrastructure Technologies Program under the Codes and Standards subprogram element managed by Antonio Ruiz.

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title**: Early-Stage Quantitative Risk Assessment to Support Development of Codes and Standard Requirements for Indoor Fueling of Hydrogen Vehicles

II. **Project Start/Finish Dates:** June 2010 to November 2012.

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** 1.0 person-yrs.

IV. **Project Leader, Principal Investigator(s), and Country:** Katrina Groth, Jeffrey LaChance, and Aaron Harris, Sandia National Laboratories (USA).

V. **Task 31 Work Plan Subtask or Activity Supported**: Subtask C - Early markets: risk identification and hazard analysis; RCS Development, Improvements in Risk Assessment Methods, and Support and Systems Safety Analysis of Hydrogen Applications

VI. **Summary:** This effort produced an early-stage QRA for a generic, code-compliant indoor hydrogen fueling facility. The goals of conducting this activity were threefold: to provide initial insights into the safety of such facilities; to recommend risk-informed changes to indoor fueling requirements in safety codes and standards; and to evaluate the quality of existing models and data available for use in hydrogen installation QRA. The work provided several recommendations for code changes that will improve indoor fueling safety. The work also provided insight into gaps in the QRA process that must be addressed to provide greater confidence in the QRA results.

VII. **Collaborations:** There was no collaboration on this work with other Task 31 participants. However, there were separate efforts in other countries to perform risk assessment of indoor hydrogen applications.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** Generation of risk-informed hydrogen codes and standards and safe hydrogen facilities.

IX. **Project Narrative:** Sandia was asked to conduct an early-stage QRA on a generic, code-compliant indoor fueling system, with the following objectives:

Objective 1: Provide screening-level assessment of the fatality risk for a generic, code-compliant indoor fueling system.

Objective 2: Provide science-based and risk-based recommendations to improve NFPA 2, Chapter 10 as possible.

Objective 3: Identify required improvements to the QRA that will provide more detailed insights than screening-level analysis.

X. **Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities:** This work identified five important gaps in the QRA process that should be addressed to improve its use in evaluating the risk in the hydrogen infrastructure:

Gap 1. A defensible probability model for ignition.

Gap 2. Probability models for gas and flame detection, and other indoor-only components.

Gap 3: Simplified models for predicting loads from deflagration and detonation for different release sizes.

Gap 4: Hydrogen-specific data for refining QRA modeling assumptions.

Gap 5: Consideration of human, software, and organizational failure drivers

Addressing these gaps would be areas for international collaboration.

XI. Acknowledgements: This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen, Fuel Cells and Infrastructure Technologies Program under the Codes and Standards subprogram element managed by Antonio Ruiz.

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title:** Vertical Jet Fires

II. **Project Start/Finish Dates:** June 2011 to April 2012

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** Not available.

IV. **Project Leader, Principal Investigaors(s) and Country:** Thomas Jordan, Germany

V. **Task 31 Work Plan Subtask or Activity Supported:** Subtask A - Physical Effects and Knowledge Gaps

VI. **Summary:** The work carried out on large scale vertical jet fires was reported in Task 31, Subtask A. For large scale storage of hydrogen underground caverns are considered in Germany. In case of simultaneous failure of the two closing valves a huge release of hydrogen might occur lasting several days. It is assumed that the release ignites early. In the analysis the radiation load on the environment, in particular close to the ground level where first responders might have to approach the release point, should be compared to a similar accident with natural gas.

VII. **Collaborations:** Models of partners have been chosen and information about the simple model has been shared at Subtask A meeting in Oslo January 2012 and at the spring meeting in Paris in April 2012.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** The project aimed at deriving a simple but most accurate simple method to determine the radiation from a vertical hydrogen jet fire based on published correlations.

IX. **Project Narrative:** The project was initiated to support another national project, where large scale underground storage of hydrogen was investigated. Correlations of SNL, UU and University of Loughborough were used to determine dimensionless numbers of a release, the length and width of the flame, the radiant fraction and finally horizontal and vertical components of the radiation over distance from the fire. Required input is the flow rate of the release and dimension of the nozzle, pipe respectively. A new formulation for the horizontal component had to be derived.

X. **Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities:** Validation data for large scale hydrogen fires is lacking.

XI. **Acknowledgements:** The work described above was funded and supported by KIT.

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title:** Flame acceleration and DDT in flat semi-open layers with concentration gradients

II. **Project Start/Finish Dates:** November 2007 to ongoing

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** Total project budget (Phase I + II): 2.3 Mio Euro, ~150 person months

IV. **Project Leader, Principal Investigtor(s), and Country:** Thomas Jordan, Germany

V. **Task 31 Work Plan Subtask or Activity Supported:** The work carried out on transient combustion behavior in flat layers was in support of Task 31, Subtask A – Physical Effects and Knowledge Gaps.

VI. **Summary:** The sigma- and lambda-criterion derived from homogeneous mixtures combusted in closed tubes have been extended to the more realistic conditions, characterized by partial confinement and inhomogeneity of the mixture composition. The extended criterion for the flame acceleration (FA) converges to the "classical" condition with full confinement, where the critical sigma equals 3.75. Similarly the deflagration-to-detonation (DDT) criterion was relaxed, i.e. larger premixed systems are required under vented conditions compared to full enclosure. Instead of 7 times the detonations cell size almost double (factor 13.5) as large premixed clouds are required for a detonation transition. It was shown that a minimum layer height of 0.6m is required to achieve a detonation without further obstruction.

The inhomogeneous mixture showed a surprising behavior. The overall behavior seems to be controlled rather by the maximum concentration instead of by the average concentration. This emphasizes the importance of accounting for the mixing processes and initial distribution of hydrogen in the flammable cloud.

VII. **Collaborations:** Information from the project was shared with Task 31 colleagues at the 2011 meeting.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** Extension of the FA and DDT to more realistic conditions and maintaining the robustness and easy application of these criteria.

IX. **Project Narrative:** Experiments were carried out in middle and large scale, up to layers of 10m length, 3m width and 0.8m height. Detailed analysis of the filling strategy was performed, to guarantee reproducible gradient mixtures. Special measurement systems have been developed which allow automated and precise measurement of the local gradients. The effective flame speed was measured for different premixed status of the cloud and different obstacle geometries. The results allowed reliable extension of the two criteria for the transient flame behavior.

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities: The maximum concentration hypothesis has to be checked for other configurations.

XI. Acknowledgements: The work described above was funded and supported by the German Forschungsbetreuung and the experimental work was conducted by Pro-Science.

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. Project Title: Two-Dimensional Flame Instabilities

II. Project Start/Finish Dates: September 2012 to August 2013

III. Estimated Level of Effort of Work Contributed to Task 31 Collaboration: 25 person months

IV. Project Leader, Principal Investigator(s), and Country: Thomas Jordan, Germany

V. Task 31 Work Plan Subtask or Activity Supported: The work carried out on flame instabilities was in support of Task 31, Subtask A – Physical Effects and Knowledge Gaps.

VI. Summary: The focus of this work is to investigate hydrogen flame behavior in a planar geometry and particularly, how the intrinsic instabilities of hydrogen flame affect its propagation in such geometry. Flame instabilities give rise to the development of a cellular structure on the surface of the flame. The cellular structure results in an increase of flame surface area and hence, promotes higher rate of fuel consumption. This results in flame acceleration (FA), which in turn could lead to the transition from deflagration to detonation (DDT). Combustion of hydrogen – air and hydrogen – oxygen mixtures were performed in between two transparent glass plates at ambient conditions. Different configurations with respect to hydrogen concentration, gap size, ignition positions and peripheral confinement were implemented. A high-speed shadowgraph method was used to visualize the flame propagation. Formation of the cellular structure was analyzed and the stretched-free laminar burning velocity was determined from 2D flame propagation. Additionally, the possibility of flame acceleration leading to the DDT phenomenon was studied.

VII. Collaborations: Information from the project was shared with Task 31 colleagues at the 2013 meeting.

VIII. Specific Technical Challenges or Barrier Being Addressed: Mechanisms for flame acceleration.

IX. Project Narrative: The experiments were performed in a glass plate assembly with various configurations with respect to H2 concentration, gap size between the two plates, ignition positions and openings along the periphery of the glass plate assembly. Two different dimensions of the glass plate assembly were used; 500 mm x 500 mm and 200 mm x 200 mm. H2 concentration was varied between 7% - 60% for H2 – air mixture and 13% - 80% for H2 – O2 mixtures Three different gap sizes were used: 6 mm, 4 mm and 2 mm. Spark electrodes were used to ignite the combustible mixtures and the position of this ignition source can either be at the top, center or at the bottom of the glass plate assembly. The openings along the periphery of the glass plate assembly were varied as all sides open, two of the sides open or only one side open. All experiments were performed at ambient conditions.

Flame propagation within the glass plate assembly was visualized using the shadowgraph method. Shadowgraph enables visualization of the invisible hydrogen combustion by casting shadows of the process. The flame propagation was recorded by a high-speed camera at 27000 fps and 40000 fps. Shadowgraph images show that for all investigated H2 mixtures, the flame surface goes through a transition from smooth surface to a cellular structure. For open wall configuration, lean H2 – air flame surface develops cellular structure in the early stage of the flame propagation and the appearance of such a structure is gradually delayed as concentration of H2 increases. With increasing gap size, the cellular structure is observed to appear earlier. For H2 – O2 mixtures, the cellular structure development shows no significant influence with varying H2 concentration and gap size. The early appearance of the cellular structure for lean H2 – air mixture is due to the two main intrinsic instabilities of flame, thermal – diffusive instability and hydrodynamic instability, namely Landau – Darrieus instability. For rich mixtures, the flames are only unstable against the hydrodynamic instability, hence the structure appears later.

The flame velocity dependence on mixture composition and gap size have been determined. Maximum velocity of 4.09 m/s is reached at 40% H2 concentration in the 6 mm gap configuration for H2 – air mixture, while for H2 – O2 mixture, the maximum velocity reached is 21.93 m/s at 66.6% H2 in the 2 mm gap configuration. Markstein lengths were determined optically to describe the influence of stretch on the flame and thermal – diffusive instability. Negative Markstein lengths were obtained for lean H2 – air mixtures (H2 concentration < 14% in this work) which indicates that the stretch results in acceleration of the curved flame propagation. Positive Markstein lengths were obtained for H2 – air mixtures containing higher H2 concentration and for all investigated H2 – O2 mixtures, indicating that the stretch causes a deceleration in the propagation of the curved flame.

In the scale of this work, flame acceleration and DDT phenomena were not observed in open wall configuration. Had the scale of the glass plate assembly been larger, DDT would occur in the open wall configuration. Nevertheless, flame acceleration leading to the transition to detonation in this work was able to be observed for H2 – O2 mixtures in configuration with partial confinement along the periphery. Flame acceleration was observed in mixtures with H2 concentration ranging between 40% and 70%. The early phase of detonation was clearly observed in configurations in which two of the sides were closed for H2 concentration ranging between 60% and 70%. The main preconditioning events for the occurrence of DDT are the reflection of shock waves from the wall and turbulent boundary layers.

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities: The maximum concentration hypothesis has to be checked for other configurations.

XI. Acknowledgements: The work was funded by KIT and supported by Pro-Science. Major contributions have been provided by Siti Nurhafizah Haji Tengah in the frame of her Master Thesis.

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title:** Hybrid Hydrogen/Dust Explosions

II. **Project Start/Finish Dates:** March 2012 to February 2014

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** ~60 person months

IV. **Project Leader, Principal Investigator(s), and Country:** Thomas Jordan, Germany

V. **Task 31 Work Plan Subtask or Activity Supported:** The work carried out on hybrid explosions was in support of Task 31, Subtask A – Physical Effects and Knowledge Gaps.

VI. **Summary:** Measurements of the explosion properties of the Be-substitute Al dust in mixtures with hydrogen have been performed. The results have shown that flames in hybrid Al/H2 mixtures in closed geometries can accelerate to fast flame propagation regimes indicating that Be/H2 hybrid mixtures can be much more dangerous than C or W/H2 mixtures, resulting even in deflagration/ detonation regimes. Comparisons of the experimental data with calculations performed using the computer code DET3D show good agreement.

VII. **Collaborations:** Information from the project was shared with Task 31 colleagues at the meetings in Oslo and Paris, 2012, and Denver 2013.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** Characterization of the explosion hazards of mixtures of hydrogen and metallic dusts.

IX. **Project Narrative:** The aim of this work is to continue the study on hydrogen/dust explosion hazards in case of a severe accident in ITER. However, the results are easily transferred to hydride hydrogen storage systems.

Previous studies concerned graphite and tungsten dusts. These studies have shown that both pure dusts could be exploded, however the required ignition energies were relatively high. On the other side mixed in hydrogen can be easily ignited by a weak ignition source as an electric spark and the hydrogen combustion is then able to initiate a dust cloud explosion.

The aim is to study the scalability of the DUSTEX - a small scale standard spherical device - results and to extend the database of Al/H2 explosion properties/regimes to medium scale.

The database is used to support and validate a computer code (DET3D) under development in KIT-IKET to model pressure loads of severe accident scenarios, e.g. in ITER.

Hybrid experiments in PROFLAM II were performed in 2013. The material used to simulate beryllium was aluminum; Al dust of about 1 micrometer grain size was tested in DUSTEX experiments.

DUSTEX test results can be summarized as follows:

- Hybrid mixtures of 1 micrometer Al dust/hydrogen/air had been tested for five dust concentrations – 100, 200, 400, 800, and 1200 g/m3 – each at 8 hydrogen concentrations stepping from 7 to 20 vol. %;
- At each dust concentration a reliable ignition occurred starting from 8 vol. % hydrogen;
- Explosion pressures ranged from 2.9 bar for the leanest mixture (8 vol. % H2/100 g/m3 Al dust) to 10.5 bar at 8 vol. % H2/1200 g/m3 Al dust;
- Pressure-rise rates ranged from 5 to 2200 bar/s (Kst from 1.4 m bar/s to 600 m bar/s);
- The lean H2/Al dust mixtures reacted in two stages: first hydrogen exploded fast, then Al dust burnt out the remaining oxygen, the latter was usually slower than the former;
- The most 'severe' mixtures were with an Al dust concentration of 800 g/m3; this value appeared to be the optimum dust concentration for pure dust/air mixtures.

Basing on these results, the test matrix for PROFLAM II tests involved mixtures with 100, 400, 800, and 1000 g/m3 Al-dust, each dust concentration to be tested at 8, 10, 12, 14, 16, 18, and possibly 20 vol. % hydrogen.

The PROFLAM test series was started with Cdust = 100 g/m3. In addition to the hybrid test results, also the values measured in pure hydrogen tests in PROFLAM were generated as reference cases. In general, the explosion behavior of these mixtures is quite similar to that observed in DUSTEX with similar mixtures.

The PROFLAM II tests with Cdust = 400 g/m3 were stopped at [H2] = 13 vol. %. At this hydrogen concentration the explosion seemed to reach another regime: the pressure rise rate in this case was enormously high – 1160 bar/s – which in Kst terms is 770 m bar/s. It has to be emphasized that this is 2.7 times higher than the value limiting the higher explosion Class 3 of 300 m bar/s, while the factor distinguishing Class 3 from Class 2 (200 m bar/s) is 1.5.

The data gained in the DUSTEX and PROFLAM facilities was used to validate the computer code DET3D. Modelling of the performed experiments was started and proceeded in parallel with the tests.. Good agreement between experiment and calculations has been observed.

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities: Initial temperatures and pressures should be varied to provide more practically relevant data.

XI. Acknowledgements

This work was supported by Fusion for Energy under the grant contract No. F4E-GRT-371. The views and opinions expressed herein reflect only the author's views. Fusion for Energy is not liable for any use that may be made of the information contained therein

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title:** H2FC European Research Infrastructures

II. **Project Start/Finish Dates:** November 2012 to ongoing

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** Not available/

IV. **Project Leader, Principal Investigator(s), and Country:** Phil Hooker, EU

V. **Task 31 Work Plan Subtask or Activity Supported:** The calls issued by the infrastructure project H2FC have been addressing topics of Task 31, Subtask A – Physical Effects and Knowledge Gaps.

VI. **Summary:** The project H2FC offers European test infrastructure to external "user groups". Furthermore it includes external partners in the networking and strategic discussions. More than 2 Mio Euro are offered for access of European research infrastructure for hydrogen technology testing with regard to performance, durability and safety issues.

VII. **Collaborations:** Within Task 31 two "user projects" for the transnational access in H2FC have been initiated and user groups have been formed.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** One user project addresses the behavior of wall attached jets, the other addresses the fire resistance of vehicle onboard hydrogen pressure vessels.

IX. **Project Narrative:** Both proposals have been evaluated positively and will be conducted in 2014.

X. **Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities:** Not applicable.

XI. **Acknowledgements:** This work is supported by H2FC European Infrastructure, which is an Integrating Activity funded by the European Commission under FP7 Capacities Programme. Grant agreement No. FP7-284522

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title:** Simple Tools

II. **Project Start/Finish Dates:** April 2012 to ongoing

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** Not available.

IV. **Project Leader, Principal Investigator(s), and Country:** Thomas Jordan, Germany, Canada, and USA

V. **Task 31 Work Plan Subtask or Activity Supported:** The work carried out on hybrid explosions was in support of Task 31, Subtask A – Physical Effects and Knowledge Gaps.

VI. **Summary:** The project Simple Tools have been initiated by representatives of Canada and Germany to translate findings of basic research into easily applicable tools for risk assessment. These tools typically are least conservative correlations, criteria, statistics, which are easily applied and provide fast and affordable answers to questions encountered in a typical risk assessment. The set of tools shall be offered via internet open and free and shall be well documented. This way recent scientific knowledge will become applicable by non-experts at affordable costs. As these tools will represent state of the art, they might be referred in flexible performance based standards.

VII. **Collaborations:** German and Canadian representatives have committed to cooperate. The work has to be financed by a mix of national and international funds. It is intended to stir further cooperation in the European and international context with this project. Possibly it will serve as a platform for a future IEA HIA safety task.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** All

IX. **Project Narrative:** First investigations of suitable platforms for the development of the Simple Tools have been done. First concepts of the systems have been developed by SNL and KIT. A Canadian application for funding has been success.

X. **Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities:** Not applicable.

XI. **Acknowledgements:** This work has been initiated by the IEA HIA Task 31 itself.

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title:** Liquid hydrogen releases

II. **Project Start/Finish Dates:** June 2009 to January 2013

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** Not available.

IV. **Project Leader, Principal Investigator(s), and Country:** Phil Hooker, UK

V. **Task 31 Work Plan Subtask or Activity Supported:** The work carried out on liquid hydrogen LH2 spills was in support of Task 31, Subtask A – Physical Effects and Knowledge Gaps.

VI. **Summary:** If the hydrogen is to progress as a fuel for transport, more hydrogen fuelling stations are required. In the short term, in the absence of a hydrogen distribution network, the most likely means of supplying the fuelling stations will be by liquid hydrogen road tanker. The development will clearly increase the number of tanker offloading operations significantly and these may need to be performed in more challenging environments with close proximity to the general public. Experimental work was commissioned by the UK Health and Safety Executive (HSE) in order to determine the hazards associated with liquid hydrogen spills onto the ground at rates typical for a tanker hose failure during offloading.

VII. **Collaborations:** Information from the project, including the explosion event (see later), was shared with Task 31 colleagues at the Spring meeting in Paris in April 2012.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** The project aimed to obtain experimental data relating to the potential hazards of liquid hydrogen leakage during tanker offloading operations within environments in close proximity to the general public (i.e. non-industrial settings) and to compare the experimental data for pool size against mathematical models.

IX. **Project Narrative:** The experimental program involved releasing liquid hydrogen from a tanker at 1 bar g via an open-ended, 20 m long, 1” nominal bore vacuum insulated hose and this resulted in a nominal rate of 60 liters per minute (70 g/s).

Measurements were made on unignited and ignited releases, including:

- concentration of hydrogen in air, thermal gradient in the concrete substrate, liquid pool formation, temperatures within the pool
- flame velocity within the cloud, thermal radiation, IR and visible spectrum video records
- sound pressure measurements
- an estimation of the extent of the flammable cloud was made from visual observation, video, IR camera footage and the use of a variable position ignition source

Unignited tests were performed in which LH2 was released in one of the following ways; a) horizontally along the ground, b) vertically downwards from 100mm above the ground, c) horizontally at a height of 860mm above the ground. Hydrogen concentration was determined from temperature measurements within the hydrogen cloud. The tests in which the LH2 impinged onto the ground all produced a pool of liquid once the ground had cooled sufficiently, usually about 2 minutes into the release, and the formation of a mixture of solidified air and liquid hydrogen was observed.

Several horizontal ground level releases were intentionally ignited, the resulting thermal radiation being measured and video records of the flame being made. In one test, the initial fire ball was followed some seconds later by a large explosion, estimated to result from the sudden combustion of several hundred grams of hydrogen. It is speculated that oxygen enrichment may have been involved in the explosion since it was not possible to replicate the phenomenon in further tests carried out during different wind conditions.

Modelling of a spreading LH2 pool was carried out using GASP (Gas Accumulation over Spreading Pools). The model performed better than expected and provided predictions of the pool radius that were in reasonable agreement with the experimental data despite the model not being able to account for the solid formation seen in the experiments.

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities: The source of the explosion is not certain. It is thought that this occurred as a result of the sudden reaction of hydrogen with the air, possibly enriched with oxygen, that was condensed on the ground. It is not clear whether the explosion took place in the gaseous or condensed phase.

XI. Acknowledgements: The work described above was funded and supported by the U.K. Health and Safety Executive (HSE).

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title:** Hydrogen Venting Under Variable Flow Conditions

II. **Project Start/Finish Dates:** July 2008 to September 2011

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** Not available.

IV. **Project Leader, Principal Investigator(s), and Country:** Phil Hooker, UK

V. **Task 31 Work Plan Subtask or Activity Supported:** The work carried out on hydrogen venting was in support of Task 31, Subtask A – Physical Effects and Knowledge Gaps.

VI. **Summary:** Safety distances for hydrogen plumes were historically derived using models developed for hydrocarbon releases. Since hydrogen behaves in a significantly different manner to that of hydrocarbons when released to atmosphere it was necessary to obtain data from hydrogen plumes for comparison with existing models. Thermal radiation was measured for ignited hydrogen plumes for a range of vent terminations designs and flow rates. Concentration measurements were taken for unignited hydrogen plumes. Thermal dose calculations were used to propose safety distances for such releases.

VII. **Collaborations:** Information from the project was shared with Task 31 colleagues at the 2011 meeting.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** The project aimed to obtain experimental data relating to the radiation from ignited hydrogen plumes and concentration profiles from unignited plumes, to compare the results with existing models and to provide a basis for reviewing existing safety distance criteria.

IX. **Project Narrative:** Experiments were carried out to investigate the effects of releasing hydrogen at various release rates to simulate emergency venting from hydrogen storage. The maximum release rate simulated a release of hydrogen from a 2 inch vent on an industrial facility. Smaller releases were also made to simulate other realistic scenarios, such as venting from forecourt type storage. There are two main aspects involved with the development of safety distances for credible hydrogen releases; the intensity of the thermal radiation from such a plume should it be ignited, and the distance downwind from the release point to the point where a flammable mixture with air no longer exists. Thermal radiation measurements, including far field up to 40 m away, were made for ignited plumes for direct comparison with models. The hydrogen plumes studied were from vertical open ended vent pipes, pipes terminating in a T-piece and also pipes with a 45° vent termination. Hydrogen concentration measurements of an unignited release from a T-piece were also made.

The test facility built at HSL fed hydrogen from a tube trailer containing 4000 m^3 of hydrogen at 228 bar through a range of flow restrictors, a flow-meter. The release point was at a height of 5.5 m and used ¾" nominal bore and 2" nominal bore vent pipes.

Meteorological measurements; air temperature, relative humidity, wind speed and direction were also measured. The heat flux measurements were used in thermal dose calculations which were then used to propose safety distances. EIGA IGC 15/06 recommends a safety/separation distance of 8 metres for a gaseous hydrogen installation from the site boundary and areas where people are likely to congregate; this distance does not conflict with the findings from these experiments. There was, however, much variability in the near field heat flux measurements. T-piece vent terminations are not recommended for use on hydrogen vent pipes due to the downward deflection of the gas stream at high exit velocities.

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities: There was much variability in the near field heat flux measurements; this would be worthy of further study.

XI. Acknowledgements: The work described above was funded and supported by the U.K. Health and Safety Executive (HSE), Shell and Statoil.

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. Project Title: Energy Technologies Institute (ETI) High Hydrogen Project

II. Project Start/Finish Dates: September 2011 to ongoing

III. Estimated Level of Effort of Work Contributed to Task 31 Collaboration: Not available.

IV. Project Leader, Principal Investigator(s), and Country: Phil Hooker, UK

V. Task 31 Work Plan Subtask or Activity Supported: Task 31, Subtask A – Physical Effects and Knowledge Gaps.

VI. Summary: The project is to benefit the manufacturers and operators of power plants which may utilize fuel containing high or variable levels of hydrogen such as gas feeds from landfill and anaerobic digesters. New modelling and large-scale experimental work will identify the bounds of safe design and operation of high efficiency CCGT (combined cycle gas turbine) and CHP (combined heat and power) systems operating on a range of fuels with high and variable concentrations of hydrogen.

VII. Collaborations: The project objectives and proposed methods were shared with Task 31 colleagues at the Spring meeting in Buxton in April 2013.

VIII. Specific Technical Challenges or Barrier Being Addressed: The project will investigate the impact of a 'flameout' in a CCGT or reciprocating engine CHP system, which may result in an explosive mixture of fuel and air being pumped into a hot exhaust system before the flameout is detected. This in turn could lead to an explosion.

IX. Project Narrative: The project goals are to increase the range of fuels that can be safely used in power and heat generating plant by identifying the boundaries of safe design and operation of power generation systems using hydrogen based fuels; and identifying improvements in the detailed design and instrumentation of hydrogen fuelled power systems in order to deliver more robust and inherently safer system designs. An experimental facility has been designed and is being commissioned at HSL. The project is ongoing.

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities: Project ongoing.

XI. Acknowledgements: The project is being carried out for the ETI in collaboration with Imperial College.

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title:** Hydrogen Incident Reporting and Lessons Learned (H2incidents.org)

II. **Project Start/Finish Dates:** 2006 - ongoing

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** Not available.

IV. **Project Leader, Principal Investigator(s), and Country:** Steven C. Weiner, USA

V. **Task 31 Work Plan Subtask or Activity Supported:** Subtask D

VI. **Summary:** Hydrogen Incident Reporting and Lessons Learned is a database-driven website (http://h2incidents.org), currently containing 211 safety event records, that facilitates the sharing of lessons learned and other relevant information gained from actual experiences using and working with hydrogen and related technologies. Incidents and near-misses are voluntarily submitted, characterized with emphasis on lessons learned, and posted without attribution. With the 2013 launch of "Hydrogen Tools, Focusing on Safety Knowledge" through Apple's App Store, the database is now available on iPad and iPhone devices. A worldwide network of interested users receives periodic notices when new safety events are posted.

International collaboration has always been a hallmark of this work; 20% of the safety event records were submitted from outside the U.S. Collaborative partners have included the International Energy Agency's Hydrogen Implementing Agreement (IEA HIA) and the member countries in the Task 31 experts' group focusing on hydrogen safety. Valuable collaborations have also been undertaken with the International Association of Hydrogen Safety (HySafe) and the European Commission's Joint Research Centre in Petten, NL who have responsibility for the Hydrogen Incident and Accident Database (HIAD). These collaborative efforts have included workshops, safety event record exchanges, conference presentations and demonstrations and a recent webinar (http://www1.eere.energy.gov/hydrogenandfuelcells/webinars.html) at the International Conference on Hydrogen Safety in Brussels, Belgium in September 2013.

VII. **Collaborations:** Steven C. Weiner, Pacific Northwest National Laboratory and the Hydrogen Safety Panel, sc.weiner@pnnl.gov; European Commission's Joint Research Centre; Task 31 member experts.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** The work on "H2incidents.org" helps the U.S. Department of Energy's Fuel Cell Technologies Office overcome one of the technical barriers identified by its Hydrogen Safety, Codes and Standards subprogram – the limited access and availability of safety data and information. Many new hydrogen fuel users and systems manufacturers lack hydrogen experience and have limited accessibility to data and documented experiences related to traditional hydrogen industrial, aerospace, and other applications. Only limited non-proprietary data on the operational and safety aspects of these technologies are easily accessible and data mining and other approaches have not been fully explored. This work also helps Task 31 meet one of its principal objectives to provide hydrogen safety knowledge and targeted information packages as a means to accelerating the adoption of hydrogen and related systems.

IX. Project Narrative: See VI. Summary, above.

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities: The sharing of safety event information and data in a publicly accessed database requires that issues surrounding proprietary, confidential and business-sensitive information be respected, addressed at the outset and dealt with in a vigilant and consistent manner. Working diligently with an "incident owner" is a key principle to be followed.

To remain vital and useful, databases and websites require a concerted effort beyond general maintenance. The content must be current, relevant to the community being served and valuable to the user. Prompt and timely responses to user feedback and inquiries are important considerations.

XI. Acknowledgements: The financial support from the U.S. Department of Energy's Fuel Cell Technologies Office (Sunita Satyapal, Director) for this project and U.S. participation in IEA HIA work on hydrogen safety is gratefully acknowledged

XII. Relevant publications and presentations (since 2010)

- Weiner, S.C. and Blake, C.W., "Safety Knowledge Tools Enhanced by International Collaboration," A White Paper of the International Energy Agency Hydrogen Implementing Agreement Task 19 – Hydrogen Safety, PNNL-19901, October 18, 2010.
- Weiner, S.C., Fassbender, L.L. and Quick, K.A., "Using Hydrogen Safety Best Practices and Learning from Safety Events," PNNL-SA-70148, International Journal of Hydrogen Energy, Volume 36, Issue 3, February 2011, pp. 2729-2735.
- Weiner, S.C. and Fassbender L.L., "Lessons Learned from Safety Events," PNNL-SA-78868, International Conference on Hydrogen Safety, San Francisco, CA, September 12-14, 2011.
- Weiner, S.C. and Fassbender L.L., "Lessons Learned from Safety Events," PNNL-SA-86551, International Journal of Hydrogen Energy, Volume 37, Issue 22, November 2012, pp. 17358-17363 (published online (http://dx.doi.org/10.1016/j.ijhydene.2012.03.152).
- Weiner, S.C., Fassbender, L.L., Blake, C., Aceves, S., Somerday, B.P. and Ruiz, A., "Web-Based Resources Enhance Hydrogen Safety Knowledge," PNNL-SA-82812, International Journal of Hydrogen Energy, Volume 38, Issue 18, June 2013, pp 7583-7593.
- Weiner, S.C., "Advancing the Hydrogen Safety Knowledge Base," PNNL-SA-91531, International Conference on Hydrogen Safety, Brussels, Belgium, September 9, 2013.
- Weiner, S.C., "What Can We Learn from Hydrogen Safety Event Databases? – H2Incidents.org," Webinar presented at the International Conference on Hydrogen Safety, Brussels, Belgium, September 10, 2013.

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title:** Hydrogen Safety Best Practices (H2bestpractices.org)

II. **Project Start/Finish Dates:** 2007 - ongoing

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** not available.

IV. **Project Leader, Principal Investigator(s), and Country:** Steven C. Weiner, USA

V. **Task 31 Work Plan Subtask or Activity Supported:** Subtask D

VI. **Summary:** A wealth of knowledge and experience related to the safe use and handling of hydrogen exists as a result of an extensive history in a wide variety of settings. Hydrogen is gaining increasing attention worldwide as an energy storage medium, for later conversion to electricity through fuel cells. This focus has introduced many new participants to research, development, demonstration, and deployment of hydrogen and fuel cell technologies and systems.

The "H2bestpractices.org" online resource captures relevant portions of that vast knowledge base of hydrogen experience and makes it publicly available to those working with hydrogen and related systems, including those just starting to work with hydrogen. Best practices, defined as a technique or methodology that has reliably led to a desired result, have been compiled from a variety of resources, many of which are in the public domain and can be downloaded directly from the references section. With the 2013 launch of "Hydrogen Tools, Focusing on Safety Knowledge" through Apple's App Store, the online manual is now available on iPad and iPhone devices.

The collaborative contributions from Task 19 member experts to this work were discussed in the referenced Task 19 white paper, *Safety Knowledge Tools Enhanced by International Collaboration*.

VII. **Collaborations:** Steven C. Weiner, Pacific Northwest National Laboratory and the Hydrogen Safety Panel, sc.weiner@pnnl.gov; Los Alamos National Laboratory; NASA; Task 19/31 member experts; Task 22, Fundamental and Applied Hydrogen Storage Materials Development.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** The work on "H2bestpractices.org" helps the U.S. Department of Energy's Fuel Cell Technologies Office overcome one of the technical barriers identified by its Hydrogen Safety, Codes and Standards subprogram – the limited access and availability of safety data and information. Many new hydrogen fuel users and system developers and manufacturers lack hydrogen experience and have limited accessibility to documented experiences related to traditional hydrogen industrial, aerospace, and other applications. This work also helps Task 31 meet one of its principal objectives to provide hydrogen safety knowledge and targeted information packages as a means to accelerating the adoption of hydrogen and related systems.

IX. Project Narrative: See VI. Summary above.

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities: To remain vital and useful, an online manual such as "H2bestpractices.org" requires a concerted effort beyond general maintenance. The content, refreshed periodically, must be current, relevant to the community being served and valuable to the user. Prompt and timely responses to user feedback and inquiries are important considerations for the project team.

XI. Acknowledgements: The financial support from the U.S. Department of Energy's Fuel Cell Technologies Office (Sunita Satyapal, Director) for this project and U.S. participation in IEA HIA work on hydrogen safety is gratefully acknowledged.

XII. **Relevant publications and presentations**

- Weiner, S.C. and Barilo, N.F., "Hydrogen Safety Panel: Shaping Safety Awareness and Practice," PNNL-SA-61902, 2008 Mary Kay O'Connor Process Safety Center International Symposium, College Station, TX, October 28-29, 2008.
- Weiner, S.C. and Blake, C.W., "Safety Knowledge Tools Enhanced by International Collaboration," A White Paper of the International Energy Agency Hydrogen Implementing Agreement Task 19 – Hydrogen Safety, PNNL-19901, October 18, 2010.
- Weiner, S.C., Fassbender, L.L. and Quick, K.A., "Using Hydrogen Safety Best Practices and Learning from Safety Events," PNNL-SA-70148, International Journal of Hydrogen Energy, Volume 36, Issue 3, February 2011, pp. 2729-2735.
- Weiner, S.C., Fassbender, L.L., Blake, C., Aceves, S., Somerday, B.P. and Ruiz, A., "Web-Based Resources Enhance Hydrogen Safety Knowledge," PNNL-SA-82812, International Journal of Hydrogen Energy, Volume 38, Issue 18, June 2013, pp 7583-7593.

Project Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title:** Hydrogen Incident Accident Database (HIAD)

II. **Project Start/Finish Dates:** 2005 - ongoing

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:**

IV. **Project Leader, Principal Investigator(s), and Country:** Daniele Baraldi, EU

V. **Task 31 Work Plan Subtask or Activity Supported:** Subtask D

VI. **Summary:** HIAD is an open communication platform collecting data on hydrogen-related undesired events (https://odin.jrc.ec.europa.eu/Hiad4/index.hiad). HIAD is a web-based database to assist all stakeholders (e.g., industry and authorities) in better understanding hydrogen-related incidents and accidents as well as the safety actions taken.

Collaborations have been undertaken within Task 31, mainly with the Pacific Northwest National Laboratory, including exchanges of safety event records, conference presentations, database demonstrations, and more recently a webinar at the International Conference on Hydrogen Safety (September 9-11, 2013, Brussels, Belgium).

VII. **Collaborations:** Daniele Baraldi, Joint Research Centre European Commission, daniele.baraldi@ec.europa.eu; International Association of Hydrogen Safety (HySafe); Steven Weiner, Pacific Northwest National Laboratory; Task 31 member experts.

VIII. **Specific Technical Challenges or Barrier Being Addressed:**

IX. **Project Narrative:** HIAD was developed to fill a knowledge gap: the lack of information and data that are related to hydrogen unintended events like incidents, accidents and near-misses. HIAD is a web-based database collecting data on hydrogen-related undesired events. Data include systems and components affected or involved, operation phase or mode, chain of events, causal relations, safety systems and emergency response, consequences of event, lessons learned. The database includes four modules: the Data Entry Module (DEM), the Data Retrieval Module (DRM), the Data Analysis Module (DAM), and the Maps module which allow viewing the geographical distribution of the events on Google maps. The events can be submitted directly by the database users into the system or alternatively can be sent to the Joint Research Centre staff who inserts the data on behalf of the event provider. The identifying information of the event, including names of companies, organizations, place of the event is not mandatory. A quality assurance process ensures the quality of all collected data into the database.

X. **Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities:** The collection of data related to incidents and accidents remains a very difficult task. Very often the owner of the information does not have a strong interest in sharing sensitive data about an event outside the companies or organizations that are directly involved in the event.

XI. Acknowledgements: The financial support from the Joint Research Centre of the European Commission is gratefully acknowledged.

XII. Relevant publications and presentations

- Moretto P. and Baraldi D., “HIAD, the European Hydrogen Incident and Accident Database” Webinar presented at the International Conference on Hydrogen Safety, Brussels, Belgium, September 10, 2013.
- Galassi M.C., Papanikolaou, E., Baraldi, D., Funnemark, E., Håland, E., Engebo, A., Haugom, G.P. Jordan, T., Tchouvelev, A.V., HIAD - Hydrogen incident and accident database. International Journal of Hydrogen Energy, 37 (22), pp. 17351-17357, 2012.
- Galassi M.C., Papanikolaou, E., Baraldi, D., Funnemark, E., Håland, E., Engebo, A., Haugom, G.P. Jordan, T., Tchouvelev, A.V., “HIAD - Hydrogen incident and accident database,” International Conference on Hydrogen Safety, San Francisco, CA, September 12-14, 2011.
- Jordan, T., Adams, P., Azkarate, I., Baraldi, D. at al., “Achievements of the EC network of excellence HySafe,” International Journal of Hydrogen Energy, 36 (3), pp. 2656-2665, 2011.
- Kirchsteiger, C., Vetere Arellano, A.L., Funnemark, E., “Towards establishing an International Hydrogen Incidents and Accidents Database (HIAD),” Journal of Loss Prevention in the Process Industries, 20 (1), pp. 98-107, 2007.

Project/Activity Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. Project Title: Numerical and experimental investigation of DDT and detonations in inhomogeneous and homogeneous hydrogen-air mixtures and in boundary layers

II. Project Start/Finish Dates: 2010/2014 to 2017

III. Estimated Level of Effort of Work Contributed to Task 31 Collaboration: (annual person-years per year) 0.5. TUC will apply for funding of one full time PhD. Student. If TUC gets the extra funding: 1.5 annual person-years per year. Special Facilities/Equipment Resources used: Internal lab and field test facilities in Norway.

IV. Project Leader, Principal Investigator(s), and Country: Knut Vågsæther, Dag Bjerketvedt, André V. Gaathaug Telemark University College (TUC); Norway

V. Task 31 Work Plan Subtask or Activity Supported:

VI. Summary: The project scope is a numerical and experimental investigation to study and quantify the possibilities of DDT in real hydrogen-air clouds from accidental release. A study of DDT in boundary layers in hydrogen-air-mixtures is also an important part of this project. Previous work for DDT in homogeneous clouds and Froude scaling laws for formation of inhomogeneous clouds is being used and developed for smooth channels and complex geometries.

The project will produce scientific research papers, continue the development of the TUC in-house simulation tool and combustion model for gas explosions and produce high speed films for better understanding the fast processes in DDT and detonations in hydrogen-air.

VII. Collaborations:

VIII. Specific Technical Challenges or Barrier Being Addressed:

- Contribute to the process of scaling from lab-scale experiments to real scale.

- A better understanding of the processes controlling DDT in both inhomogeneous and homogeneous gas clouds.

- A better simulation tool/model for predicting DDT in hydrogen-air.

- A contribution to the research of quantifying the possibilities for DDT in hydrogen-air explosions.

IX. Project Narrative: See VI. Summary above.

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities:

XI. Acknowledgements:

Project/Activity Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title:** Risk Mitigation

II. **Project Start/Finish Dates:** January 2010 to ongoing

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** The combined total effort by the JRC, NREL and UQTR personnel for the quantitative assessment of micro-machined hydrogen sensors is estimated as 1 person-year. **Special Facilities/Equipment Resources used:** Sensor evaluations and performance assessments were performed by personnel at the NREL and the JRC Sensor Test Facilities.

IV. **Project Leader, Principal Investigator(s), and Country:** William Buttner, USA, Eveline Weidner, EC/JRC

V. **Task 31 Work Plan Subtask or Activity Supported:** Subtask C

VI. **Summary:** In support of hydrogen infrastructure deployment, sensor testing facilities were established to ensure that hydrogen sensors would be available to meet end-user requirements. Often sensor performance either does not meet end-use needs or deviates from that specified by suppliers. It has also been observed that many difficulties encountered by end-users arise from improper use of hydrogen sensors. Independent measurement of sensor performance is critical to verifying that performance metrics specified by the manufacturer are repeatable and that test systems developed in different laboratories produce comparable results. Advanced sensing element designs with enhanced performance are being commercialized. Micro-machined hydrogen sensing elements have shown dramatic improvements in response times, but independent tests have also shown degradation in performance metrics for some sensors, especially dynamic measuring range, relative to their conventional analogs. This collaborative work, which assessed the improvements brought by micro-technology as well as its shortcomings, was performed to provide guidance to end-users.

VII. **Collaborations:** Lois Boon-Brett, Valerio Palmisano, JRC, EU; Robert Burgess, Matthew Post, Carl Rivkin, NREL, USA; Frederic Domingue, Hatem El Matbouly, University of Quebec a Trois-Rivieres, CN.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** To identify gaps between end-user requirements and sensor performance.

IX. **Project Narrative:** Within the framework of Task 31, an exchange of information pertaining to the development, selection and correct deployment of hydrogen safety sensors was collaboratively undertaken by the U.S. Department of Energy National Renewable Energy Laboratory (NREL) and the Joint Research Centre (JRC) Institute for Energy and Transport. Both NREL and the JRC have established histories in performance testing of hydrogen sensors under conditions representative of typical hydrogen applications. Through interactions facilitated by the Task 31 Experts Meetings, the sensor collaboration was expanded to include researchers from the Natural Sciences and Engineering Research Council of Canada's Hydrogen Canada Strategic Research Network with expertise in microfabrication and microelectromechanical systems (MEMs), including the development of micro-machined hydrogen sensors.

To evaluate the performance of commercial and emerging hydrogen detection technologies, an inter-laboratory comparison was performed at NREL and the JRC. The goal was the cross-validation of the respective hydrogen sensor test facilities and methodologies through the demonstration of inter-laboratory consistency. The testing program was completed by end of 2012 and the results showed comparable laboratory to laboratory repeatability for sensor performance assessments; preliminary results were published as a JRC Technical Report {*Interim Report of the SINTERCOM Project*, G. Black et al, EUR24843 EN (2011)} The excellent inter-laboratory consistency on performance measurements affirms the accuracy and capability of the respective sensor test laboratories.

Gaps between end-user requirements and sensor performance still exist. For example, DOE has established a target response time of 1s for hydrogen safety sensors. One strategy employed by sensor developers to improve response time is to miniaturize the geometric dimensions of the sensing element. Micro-machined hydrogen sensing elements for numerous platform types are now commercially available (e.g., catalytic - CAT, thermal conductivity - TC, metal oxide - MOX). Micro-machined hydrogen sensing elements for each of these platform types have shown dramatic improvements in response times, although achievement of the 1-s response time remains elusive. Furthermore, economy of scale production leading to significant cost reductions can be potentially achieved using micro-machining manufacturing techniques.

In 2011, JRC, NREL together with the Laboratoire de microsystèmes et télécommunications, Université du Québec à Trois-Rivières (UQTR) initiated a study on micro-machined hydrogen sensors. A market survey was performed to identify commercial-off-the-shelf hydrogen sensors and sensing elements available in both micro-machined and conventional formats. TC sensors with conventional and micro-machined sensing elements were purchased and tested. MOX sensing elements without commercial control circuitry were also purchased and tested. Tests were performed by a graduate student from UQTR at the JRC, with similar tests performed at NREL. Evaluations were performed using test protocols analogous to those recommended in international standards and included linear/dynamic range and short-term stability/repeatability measurements. In addition, sensor response and recovery time measurements were performed using a dedicated test fixture and validated test method.

The performance of the micro-machined TC sensing element was equal or superior to its conventional counterpart on all critical analytic metrics. The micro-machined MOX devices showed improvement in response time, but also exhibited degradation in some performance metrics, especially dynamic measuring range, relative to their conventional analogs. There is, however, promise in the approach of micro machining hydrogen safety sensors. The micro-machined sensors all exhibited dramatically improved response times. Economy-of-scale manufacturing techniques afforded by micro-machining will ultimately reduce the unit cost of the sensing element. The potential for better control of the manufacturing process is expected to improve device-to-device repeatability and overall performance.

Major accomplishments/Products and schedule for each: The results of the tests on micro machined sensors have shown that advanced manufacturing techniques (e.g., micro-machining) do not always lead to improved performance. It is noted that the study was not a comprehensive assessment of all micro-machined sensor models, but was based on representative samples for various platform types. The performance of the micro-machined TC sensing element was equal or superior to its conventional counterpart on all critical analytic metrics. However, this was not the case for the commercial micro-machined MOX sensing elements.

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities: Some manufacturers of commercial sensing devices seem to have overly focused on response time, paying less attention to other critical sensor metrics. Many commercial hydrogen micro-machined sensing elements suffer severe degradations in some critical metrics relative to their conventional analogs, including long- and short-term stability, dynamic range, robustness to harsh environments, and repeatability. Additional testing performed at independent laboratories could provide feedback on test results to manufactures, which may help them to improve on these shortcomings.

Cross-sensitivity and robustness against potential poisons are key challenges for developers of gas sensors. In the framework of the ongoing collaboration between NREL and JRC investigations are focused on assessing sensor reliability in the presence of species other than the target gas. In addition, the potential of utilizing oxygen sensors for the detection of hydrogen will be evaluated jointly by NREL and JRC.

The suitability of wide area monitoring versus point sensors for monitoring the accidental release of hydrogen will be investigated as part of the NREL/JRC collaboration.

XI. Acknowledgements: The JRC - Institute for Energy and Transport was supported by the European Commission. NREL was supported by the U.S. DOE Energy Efficiency & Renewable Energy, Fuel Cell Technology, Safety Codes and Standards Program. The UQ received support through the Engineering Research Council of Canada (NSERC).

Project/Activity Summary

IEA Hydrogen Implementing Agreement

Task 31 - Hydrogen Safety

I. **Project Title:** BIP – IEA HIA Hydrogen Safety Collaboration with GexCon and TUC

II. **Project Start/Finish Dates:** January 2011 to December 2013

III. **Estimated Level of Effort of Work Contributed to Task 31 Collaboration:** From Telemark UC effort was about 1 person-year each year. From GexCon the effort was about 0.75 person years each year. Total about 5,25 person years.

IV. **Project Leader, Principal Investigator(s), and Country:** Leaders: Prankul Middha, Trygve Skjold**. Investigators:** Prankul Middha, Trygve Skjold, Olav R. Hansen, Idar E. Storvik, Deiveegan Muthusamy, Bjørn Lilleberg, Vagesh Narasimhamurthy, Helene H. Pedersen, Dag Bjerketvedt, André V. Gaathaug, Knut Vågsæther. Norway.

V. **Task 31 Work Plan Subtask or Activity Supported:** Mostly task A, but also smaller parts can be in subtasks B, C and D.

VI. **Summary: Telemark UC:** Experimental and numerical investigation of flame acceleration and transition to detonation (DDT) in complex geometries. Experiments in channels with multiple obstacles is planned to investigate the mechanisms of flame acceleration and DDT for flame obstacle interactions. Numerical simulations with the TUC-CFD code for compressible reactive flow to get better understanding of the investigated mechanisms. Simplified models for reaction rates i validated with these experiments. **GexCon:** The work done is primarily numerical involving continuing validation against experimental data for situations that have not been covered previously e.g. high initial temperatures and further development of the CFD tool FLACS in several important areas e.g. liquid releases, fires and DDT. GexCon has also performed experiments with hybrid mixtures of hydrogen and silicon.

VII. **Collaborations:** The work was a joint effort of GexCon and TUC.

VIII. **Specific Technical Challenges or Barrier Being Addressed:** The technical problems addressed were flame acceleration and DDT in hydrogen-air clouds and improvement of FLACS as a risk assessment tool for hydrogen safety.

IX. **Project Narrative:** Objectives:

- The improvement of our understanding of hydrogen dispersion and explosions through experiments and development and validation of reactive compressible CFD-models.
- The improvement of risk modeling tools and procedures for hydrogen applications.
- Active contribution to new activity to model accidents and incidents using CFD to try to demonstrate what happened, to show what could potentially have happened, and how it could be mitigated.

The project was able to produce experimental data for flame acceleration and DDT in hydrogen-air clouds. The results were able to increase our knowledge and understanding of the physical processes in a gas explosion in hydrogen-air. The data was/will be used as validation data for CFD-codes (FLACS and TUC-CFD code). The FLACS software was improved for risk assessment related to hydrogen safety including effects of release, dispersion, fire and explosions.

X. Unresolved or Outstanding Technical Issues and Recommendations for Future Collaborative Activities: Some recommendations for future work: Research on quantitative description of transition to detonation in hydrogen-air mixtures and a quantitative description of instabilities that affect flame acceleration. Effects of inhomogeneous gas clouds on flame acceleration.

XI. Acknowledgements: GexCon and TUC gratefully acknowledge the financial contribution (50 % funding) from the Norwegian Research Council.