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1 Introduction

The International Energy Agency (IEA) Annex 19 on Hydrogen Safety was established in 2004 to facilitate the hydrogen safety codes and standards development process. Organizationally, Annex 19 is divided into three subtasks: Risk Management (Subtask A), the Testing and Experimental Program (Subtask B), and Targeted Information Packages for Stakeholder Groups (Subtask C). In the present paper we summarize the current status and results of Subtask B, the Testing and Experimental Program. A key element in this program is the identification and development of experimental databases that are relevant to accident scenarios in real systems. Such databases are integral to a better understanding of the consequences of such accidents as well as to the validation of models developed to predict the risks and hazards associated with the accidents. A number of research groups are active in this program and include groups from Europe, Canada, Japan, and the United States. In this paper, an overview of each group's effort, the methodology and the current status of databases in the various areas are provided. Further links to details of the work, links to relevant references and information on the availability of databases are provided. Finally, an evaluation of current data gaps is given by the authors to provide greater insight into future research needs and directions.

2 United States Contribution to Experimental Data Relevant to Hydrogen Safety Standards Development

2.1 Sandia National Laboratories*

Sandia's work on hydrogen safety supports the Safety, Codes, and Standards element of the U.S. Department of Energy's Hydrogen Fuel Cells and Infrastructure Technology Program. The goal of the work is to provide the necessary experimental data and analysis to provide a sound technical basis for the development of hydrogen safety, codes, and standards.

Initial experimental work at Sandia began in 2002 and focused on quantifying the hazards associated with unintended releases of hydrogen from high-pressure gaseous sources. Experiments were performed with SRI International at their Corral Hollow test site near Livermore California to measure the flame length and radiative heat flux from large-scale hydrogen jet flames [1, 2]. This data was used to develop a predictive capability for large-scale hydrogen jet flame thermal radiation based on experimentally verified correlations and engineering models [3]. In 2007, a set of large-scale experimental tests were performed to characterize the effectiveness of barrier walls to mitigate hydrogen jet flame hazard [4]. A total of 4 different barrier configurations were evaluated using high-speed video and other suitable transducers to characterize the flame wall interactions. A second set of barrier experiments was performed in 2008 to study the effect of the ignition delay time (the time between the beginning of the release and ignition) on the amount of ignition overpressure generated [5, 6].

In addition to investigating high-momentum choked-flow releases of hydrogen, Sandia has also experimentally investigated the slow-leak regime where buoyancy can significantly affect the concentration decay and trajectory of an unignited hydrogen leak [7, 8]. Laboratory scale experiments have been performed where Planar Laser Rayleigh Scattering (PLRS) was used to measure the instantaneous concentration field in vertical and horizontal buoyant hydrogen jets. Particle Image Velocimetry (PIV) was also used to characterize the velocity. This database provides a good test for the validation of models for unintended releases of hydrogen where the effects of buoyancy are important.

Laboratory scale experiments have also been performed to study the lean ignition limits of hydrogen/air mixtures in turbulent jets using a non-intrusive laser ignition source [9]. As part of these experiments Planar Laser Rayleigh Scattering was used to measure the instantaneous hydrogen concentration field in the jet and this data was correlated with observations of ignition and jet light-up.

In many unintended gaseous hydrogen releases where ignition has occurred, the ignition source is well known (for example a nearby open flame, or an electrical spark). However, for a large number of reported incidents the ignition source has not been identified. These events are often referred to as auto-ignition events. Two of the most likely ignition sources for these events include shock heating of the resulting hydrogen/air mixture and ignition due to

* Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94-AL85000.

electrostatically charged particles. In collaboration with Dryer [10] of Princeton University Sandia has implemented a combined experimental and modeling program to identify the potential role of shock heating as an auto-ignition source. In addition, Sandia has worked with SRI International to experimentally study electrically charged particles as a source of auto-ignition [11].

Testing and modeling have also recently been performed to investigate gaseous releases from hydrogen fuel-cell vehicles in tunnels. A series of half-scale experiments has recently been completed at the SRI Corral Hollow facility to measure hydrogen concentration and ignition delay overpressure in a tunnel resulting from the release produced by activation of the simulated PRD (pressure release device) on a scaled model of a gaseous hydrogen vehicle [12].

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2.2 National Renewable Energy Laboratory

The United States Department of Energy’s National Renewable Energy Laboratory (NREL) in Golden, Colorado has supported the International Energy Agency (IEA) Annex 19 for several years through the Hydrogen Safety, Codes and Standards Program research activities. NREL, in collaboration with Sandia National Labs and other national laboratories, is responsible for the implementation of a national agenda for hydrogen codes and standards [1].

The collection and dissemination of research, development, and demonstration data for the purposes of the development of codes and standards is included in the objectives of the national agenda. As a result, hydrogen safety information and data have been collected to create a Hydrogen Safety Bibliographic Database [2] that is available to the general public through NRELs web site [3]. In addition to the bibliographic database, NREL also participates in several learning demonstrations through which operational and safety data is collected and disseminated [3].

The bibliographic database is currently comprised of 748 hydrogen safety-related references. The content is reviewed for accuracy and updated on a yearly basis. The web-based database includes a “suggested additions” feature which allows users to recommend additions to the database which are not present. A major highlight of NRELs collaboration with the IEA Annex 19 tasks is the effort to parallel the data resources contained in the HySafe Database for hydrogen safety information. In 2008, a complete review of each database was conducted to ensure that all information was concurrent in each database. Regular updates are provided to the Annex 19 members. As a result, the bibliographic database also appears as a resource in the IEA Task 19 HyTex Database.

Hydrogen safety information is also collected and disseminated through three learning demonstration projects:

- Hydrogen Fuel Cell Vehicle and Infrastructure Learning Demonstration [4]
- Hydrogen Fuel Cell Bus Evaluations [5]
- Early Fuel Cell Market Demonstrations (Forklift Operations) [6]

These projects involve gathering extensive data, including safety information, from the systems and components under real-world conditions, analyzing these detailed data, and then comparing results to technical targets. While the raw data are protected by NREL, analysis results are aggregated into public results called composite data products. These public results show the status and progress of the technology and include safety-related information. Regular updates are provided by NREL to the Annex 19 members where the information can be used as a resource to contribute to the understanding of the risks and hazards associated with the use of hydrogen.

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2.3 National Institute of Standards and Technology (NIST) Testing and Experimental Program for Hydrogen Fire Safety

NIST has a research program designed to provide experimental data, understanding, and model validation to support code development for the safe utilization of hydrogen in enclosed spaces. Current efforts are focused on hydrogen-fueled vehicles parked inside residential garages, but the results are applicable to other types of systems, e.g., residential fuel cells for power generation.

Efforts are focused on two particular problems: 1) the mixing and combustion behavior of hydrogen in enclosed spaces as the result of an unintended release and 2) the development of an experimental system for testing hydrogen sensors which incorporates potential interferents. The research is a coordinated effort involving in-house research, academic research grants, and contractor experimentation.

2.3.1 Mixing and combustion behavior of unintended releases of hydrogen

A series of experiments designed to characterize the mixing behavior of hydrogen within and subsequent removal from a typical residential garage following unintended releases has been carried out at NIST using helium as a surrogate. A study of the mixing behavior of helium within an idealized ¼-scale two-car residential garage was designed to provide reference data for validating mixing models and an improved understanding of the mixing and loss processes. The tests involved scaled releases of helium equivalent to 5 kg of hydrogen over one or four hour periods into an enclosure with a vent(s) on the front face. Vent areas were scaled to provide air exchange rates with the surroundings typical of actual garages in the United States. Additional parameters varied include the helium release location (near the floor and ceiling in the center and near the floor in the rear), vent configuration and size (two single vents with different areas located at the center of the face and a face with two vents located near the floor and ceiling). Results have been reported at a recent symposium and will appear shortly as a NIST Technical Note incorporating electronic files of the experimental measurements.

A continuing series of measurements involves the release of helium into a real-scale garage attached to an environmental test house at NIST. The focus of these measurements is the mixing behavior of the surrogate gas within the garage, the role of ambient weather conditions on the mixing within and removal of the helium from the garage, and characterizing the penetration of helium into the attached structure.

NIST contracted with Southwest Research Institute to perform a series of experiments in which hydrogen was released into a full-scale two car garage at a rate corresponding to 5 kg/hour. These tests were designed to characterize the mixing behavior of hydrogen in a real-scale garage exposed to the elements and the combustion behavior following ignition after the build up of hydrogen. Hydrogen concentrations during the releases were tracked using a series of eight sensors spanning heights from the floor to the ceiling. When hydrogen volume fractions at a position near the ceiling reached specified levels ranging from 8% to 29%, the mixtures were ignited. The subsequent combustion behavior was characterized using a combination of high-speed pressure probes, thermocouples, and visible and infrared videography. Twenty-five tests were done with 19 involving an empty garage and 6 with a vehicle parked inside the garage. The results of this investigation will be released shortly by NIST as a Government Contractors Report. Additional analysis of the findings is being performed by NIST researchers.

NIST awarded research grants to two university research groups to investigate the mixing and combustion behavior of hydrogen escaping from a pin-hole opening and the potential for catalytic surfaces to ignite hydrogen/air mixtures. The findings of the former study have been incorporated into a draft standard prepared by the Society of Automotive Engineers.

2.3.2 Hydrogen sensor characterization and testing

NIST has a long history of testing smoke detectors. This expertise has been utilized to develop a facility for performance testing of hydrogen sensors known as the Hydrogen Detector Environment Evaluator (HyDEE). This facility is based on a small, low-speed temperature-controlled wind tunnel with an air flow to which known concentrations of hydrogen and a variety of other gases and vapors can be added. The response of a sensor is determined when exposed to known hydrogen concentrations in the presence of a range of additional gases and vapors representing nuisance and obfuscating or sensor-poisoning substances. Testing is underway to characterize the behaviors of a variety of types of sensors to a wide range of conditions in the HyDEE. The ultimate goal is to identify a range of ambient conditions appropriate for standards testing of hydrogen sensors.

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3 United Kingdom Contribution to Experimental Data Relevant to Hydrogen Safety Standards Development

Over the past eight years, work conducted in the United Kingdom has contributed greatly to the body of experimental data relevant to hydrogen safety. At the 2002 WHEC in Montreal, Shell presented a paper on Safety Considerations in Retailing Hydrogen [1]. Although industry knew how to handle hydrogen safely in an industrial setting, retailing hydrogen for fuel-cell vehicle applications presented new challenges due to the very high storage pressures involved and the close proximity of the public.

Much of the experimental work in the UK has been conducted at the Health & Safety Laboratory, Buxton (HSL), and funded by the Health & Safety Executive (HSE) and Shell.

When stored as a high pressure gas, the hazards associated with jet releases from accidental leaks must be considered and these were the first to be studied experimentally. The early work was limited to release pressures of up to 15 MPa, and data on the characteristics of both ignited [2] and unignited [3] jet releases were reported.

In 2004 Shell initiated a major study on the explosion hazards posed by hydrogen leaks, co-funded by HSE, ExxonMobil, and BP. Explosion experiments were conducted in environments replicating those found on retail stations, and included both 'worst case' pre-mixed hydrogen-air clouds and high-pressure (up to 40 MPa) jet releases of hydrogen. The results provide comprehensive data sets of measured overpressures that can be used to test and validate explosion models necessary for hazard assessments [4][5][6].

Although the early work described above was focused on retailing hydrogen for vehicle application, more recent work has specifically addressed installation permitting for hydrogen and fuel-cell stationary applications in the European project HyPer [7]. Experimental data has been reported on the consequences of jet releases [8] and the efficacy of barriers in reducing separation distances [9].

There is anecdotal evidence that leaks of high-pressure hydrogen often spontaneously ignite. This is important because a spontaneously igniting leak will always result in a jet fire rather than accumulate and possibly result in an explosion. The HSL have reviewed this phenomenon [10] and it is the subject of ongoing study.

Other ongoing studies to address knowledge gaps are: hydrogen venting and liquid hydrogen hazards. Vents are an essential part of the safety system on hydrogen installations and they must be located to minimize the hazards posed by emergency venting. The HSL have produced a critique of the literature on this subject [11] and experiments are in progress to quantify the hazards of both un-ignited and ignited vents. Liquefied hydrogen is one of the options for transporting and storing hydrogen in bulk. The HSL have published a position paper on this subject [12]; there is a dearth of data and plans are in place for experiments to address this.

Hydrogen may also be transported and used in a mixture with natural gas. Experimental data has been generated in the UK on the hazards posed by mixtures of hydrogen and natural gas as part of the European project Naturalhy. This project studied many aspects including explosions in congested regions [13], and in vented confined explosions [14].

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4 France Contribution to Experimental Data Relevant to Hydrogen Safety Standards Development

Work on hydrogen energy safety was initiated in France in 1999 with a project on mechanical and thermal resistance of high pressure composite hydrogen cylinders for use in road vehicles (Figure 1A). This work was funded by the European Commission and handled by CEA (Commissariat à l'Energie Atomique), INERIS and Air Liquide [Chaineaux et al., 2000].

During the same period, INERIS (National Institute of Industrial Environment and Risks) performed experimental work funded by the French Ministry of Environment. Instrumented atmospheric dispersion experiments of massive spillage of liquid H2 were performed [Proust et al., 2000]. The overpressures and flame velocity generated by stoichiometric quiescent volume explosion were also studied (Figure 1B).

Moreover, in the framework of another French ministry project, INERIS has setup large-scale fully instrumented experiments to study the formation of flammable clouds resulting from a finite duration release of hydrogen (Figure 1C) in a quiescent room (80 m^3 chamber) [Lacome et al., 2007]. The experimental results show that for the subsonic jet, stratification appears at the top. A diffusion phase follows this stratification and, for all the tested cases the concentration became homogeneous after four hours.

In 2005, the ANR (French National Research Agency) was founded. The National Action Plan on Hydrogen and Fuel Cells Program (PANACHE) has supported 4 safety related projects: DRIVE, HYDROMEL, HYPE and DIMITRHY. These projects will be detailed in the following paragraphs.

The project DRIVE (Experimental Data for the Evaluation of hydrogen Risks onboard vehicles, the Validation of numerical tools and the Edition of guidelines) was managed by INERIS with CEA, PSA and IRPHE as partners. It investigated experimentally different types of leaks and the dispersion of hydrogen either inside the vehicle or outside the vehicle in the most critical situation when the vehicle is parked in an enclosed space such as a private garage. The build-up mechanisms of an explosive atmosphere, including the effects of confinement and ventilation mixture were studied in detail in the CEA Garage installation (Figure 1D) [Gupta et al., 2007; Cariteau et al.. 2009]. Tests of deflagration in simulated car motor area were performed by INERIS in order to define maximum tolerable explosive volumes for various leakage environments. Experimental work was also performed by INERIS on jet flames providing data on hydrogen flame length and on hydrogen flame radiation for some severe scenarios [Proust et al., 2009]. The ignition potential of some electrical and mechanical components and the leak potential of aged fittings were also assessed by INERIS. Impinging jet dispersion of classical obstacles (cylinder, sphere…) is also investigated by IRPHE in sonic and subsonic regimes [Dubois et al., 2009].

The Hydromel project is focused on safety aspects related to addition of hydrogen in natural gas transportation network. The consortium is coordinated by INERIS with CEA, Air Liquide, GDF-SUEZ, Icare (CNRS Orléans), LCD (CNRS Poitiers) as partners. The phenomenological program was dedicated to determine specific combustion properties of H2 / NG: ignition delays, laminar flame velocities (Figure 1E), flame acceleration patterns (Icare – Yahyahoui et al., 2009), detonation cell sizes, deflagration to detonation lengths (LCD-Sorin et al., 2009), and flame radiation parameters (Studer et al., 2009b).

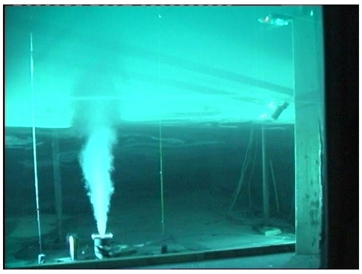
The HYPE project (PSA, CEA and Air Liquide) is focused on high pressure composite cylinder behavior in fire. Cylinder durability experiments of unprotected cylinders in classical liquid hydrocarbons pool fires are performed by INERIS. Moreover, specific highly instrumented experiments to understand heat transfer to the cylinder have also been included in the program.

The DIMITRHY (Data and instrumentation for hydrogen risk mitigation in public applications of fuel cell systems) (CEA, INERIS, AIR LIQUIDE, PSA, HELION, IRPHE) project follows on from the DRIVE project. The work program is mainly focused on mitigation strategies for the formation of explosive atmosphere by ventilation (natural and forced) and for the reduction of explosion consequences by reducing the confinement of the explosion through optimal vent sizing. Dispersion and explosion experiments will be performed by CEA and INERIS. Moreover, advanced modeling will also be used to orient and analyze the experimental work.

The project H2E (Hydrogen Horizon Energy) led by AIR LIQUIDE and funded by OSEO has been launched mid-2009. The risk and safety part of the project (in collaboration with CEA, INERIS, and LCD) will be presented in details in a specific article.

A

B



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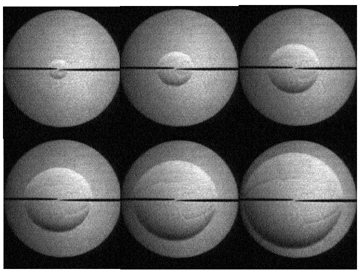

E

F

Figure 1: Photos representative of the projects.

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5 Japan Contribution to Experimental Data Relevant to Hydrogen Safety Standards Development

5.1 Fire safety evaluations of vehicles equipped with hydrogen fuel cylinders: Comparison with gasoline and CNG vehicles

To verify the fire safety of compressed hydrogen vehicles, fire tests have been conducted on vehicles that use compressed hydrogen, compressed natural gas (CNG), and gasoline as fuels. The vehicle fire evaluations compared temperatures around the vehicles and the cylinders, the internal pressure of the cylinders, the radiation heat fluxes around the vehicles, the sound pressure levels when the pressure release device (PRD) was activated, and the damage to the vehicles and surrounding flammable objects. Results of the tests indicate that vehicles equipped with compressed hydrogen gas cylinders are not more dangerous than CNG or gasoline vehicles in the event of a vehicle fire [1].

5.2 Hy-SEF: Hydrogen and Fuel Cell Vehicle Safety Evaluation Facility

A new comprehensive facility was constructed for the evaluation of hydrogen and fuel cell vehicle safety at the Japan Automobile Institute by METI and NEDO [2]. The new facility includes an explosion resistant indoor vehicle fire test building with sufficient strength to withstand an explosion of a high pressure hydrogen tank of 260 litre capacity and 70 MPa pressure. The facility has an exhaust gas cleaning system and enough space to observe vehicle fire flames of not only hydrogen but also other conventional fuels, such as gasoline or CNG. The building is 18 m in diameter, 16 m high, and the walls are made of 1.2 m thick reinforce concrete covered on the inside with steel plate. The following experimental testing program performed in the facility is summarized below. The program verifies the validity of the fuel leakage standard [3] for the collision of hydrogen vehicle.

5.3 Dispersion and ignition behavior of leaks from a hydrogen-fueled vehicle

To verify the fuel leakage standard hydrogen was leaked from the under floor of a vehicle at a flow rate exceeding 131 NL/min, which is the allowable hydrogen leakage rate from the collision of a compressed hydrogen fuelled vehicle in Japan. The resulting distribution of the hydrogen concentration in the engine compartment and the dispersion of hydrogen after stoppage of the leak were investigated. In addition, ignition tests were also conducted and the effects on the surroundings (mainly for people) were investigated to verify the safety of the allowable leakage rate. The tests demonstrated that if hydrogen leaks from the under floor of a vehicle at a flow rate of 1000 NL/min and is ignited in the engine compartment, people around the vehicle will not be seriously injured. Therefore, a flow rate of 131 NL/min, the allowable fuel leak rate for the collision of compressed hydrogen fuelled vehicles, assures a sufficient level of safety [4].

Figure 2: **Photograph of Hy-SEF Facility.**

5.4 Gaps in the experimental data base and future plans to fill these gaps

Some fire safety knowledge gaps related to hydrogen-fueled vehicles have been identified and are discussed below. These knowledge gaps are currently being investigated in research projects commissioned by NEDO.

When a jet flame is formed by fire activation of the PRD on a hydrogen-fueled vehicle, it is not known whether it is better for first responders to extinguish the flame or to continue to cool the hydrogen containers with water cannon without extinguishing the flame. The risk of rupture of the compressed hydrogen containers must be suppressed and testing methods need to be developed to insure this. In addition, the risk of fire spread to vehicles parked adjacent to the hydrogen-fueled vehicle is unknown and needs to be investigated. The combustion behavior of the hydrogen gas and surrounding materials is unknown for the case where a hydrogen-fueled vehicle is parked in an enclosure and leaked hydrogen gas penetrates into surrounding porous materials such as the walls and ceiling.

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